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Natural gas from shale formation – The evolution, evidences and challenges of shale gas revolution in United States

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ABSTRACT

Extraction of natural gas from shale rock in the United States (US) is one of the landmark events in the 21st century. The combination of horizontal drilling and hydraulic fracturing can extract huge quantities of natural gas from impermeable shale formations, which were previously thought to be either impossible or uneconomic to produce. This review offers a comprehensive insight into US shale gas opportunities, appraising the evolution, evidence and the challenges of shale gas production in the US. The history of US shale gas in this article is divided into three periods and based on the change of oil price (i.e., the period before the 1970s oil crisis, the period from 1970s to 2000, and the period since 2000), the US has moved from being one of the world's biggest importers of gas to being self-sufficient in less than a decade, with the shale gas production increasing 12-fold (from 2000 to 2010). The US domestic natural gas price hit a 10-year low in 2012. The US domestic natural gas price in the first half of 2012 was about \$2 per million British Thermal Unit (BTU), compared with Brent crude, the world benchmark price for oil, now about \$ 80–100/barrel, or \$14–17 per million BTU. Partly due to an increase in gas-fired power generation in response to low gas prices, US carbon emissions from fossil-fuel combustion fell by 430 million ton CO_2 – more than any other country – between 2006 and 2011. Shale gas also stimulated economic growth, creating 600,000 new jobs in the US by 2010. However, the US shale gas revolution would be curbed, if the environmental risks posed by hydraulic fracturing are not managed effectively. The hydraulic fracturing is water intensive, and can cause pollution in the marine environment, with implications for long-term environmental sustainability in several ways. Also, large amounts of methane, a powerful greenhouse gas, can be emitted during the shale gas exploration and production. Hydraulic fracturing also may induce earthquakes. These environmental risks need to be managed by good practices which is not being applied by all the producers in all the locations. Enforcing stronger regulations are necessary to minimize risk to the environment and on human health. Robust regulatory oversight can however increase the cost of extraction, but stringent regulations can foster an historic opportunity to provide cheaper and cleaner gas to meet the consumer demand, as well as to usher in the future growth of the industry.

Contents

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1. Introduction

1.1. Introduction of US shale gas revolution

The biggest energy story that has happened in the 21st century so far is the extraction of natural gas from shale rock formations in the United States [1–19]. The combination of horizontal drilling and hydraulic fracturing enables the extraction of huge quantities of natural gas from impermeable shale formations, which were previously thought to be either impractical or uneconomic [4,20,21]. The extraction of shale gas has transformed the US energy landscape. About 10 years ago, the decline of conventional natural gas output indicated that the US's economically recoverable natural gas reserves were in long term decline [22–24]. However, extraction of natural gas from shale formation has not only offset the decline of conventional gas output, but has resulted in the growth of total natural gas production. The US is estimated to possess a 100-year supply of natural gas at current consumption rates [1,5,11]. In addition, partly due to shale gas replacing coal-fired power plant generation, the International Energy Agency (IEA) reported that carbon dioxide from fossil fuel consumption in the US has fallen by 430 million ton from 2006 to 2011 (7.7%), the largest reduction of all countries or regions surveyed [25]. Despite its far greater efforts to tackle climate change, the carbon reduction in the European Union (EU) is less than that of the US, partly because of an increase in coal-fired power generation in response to Europe's high gas price, the failure of its emissions trading policies and the phasing out nuclear energy [25–27].

Many other countries, such as China [28], India [29], Poland [30], South Africa [31], Australia [32], Ukraine [33], and UK [34,35], are at the early stages of evaluating their shale gas resources. Many of these countries are attempting to cope with the growing energy demand while attempting to reduce their dependence on imported fossil fuel. Most notably, China, the world's biggest energy consumer [36] and the world's largest shale gas resource holder [37], has set an aggressive plan to follow America to boost its shale gas output from near zero in 2012 to 6.5 billion m^3/year by 2015 and to 80–100 billion by 2020, or a quarter of its total gas consumption [28,38–40].

However, the rise of shale gas has raised environmental concerns [1,3,41–47]. Hydraulic fracturing has been criticized for polluting water [41,42,45,48–56], emitting more greenhouse gas caused by fugitive methane [57–62], causing detrimental health impacts [46,63,64] and even to cause earthquakes [65–67]. If the shale gas industry does not work harder to address environmental safety, sustainability and health impacts, the revolution risks being limited or even halted [68–73].

Table 1
A selected of references of evolution, evidence and challenges of US shale gas revolution.

Item	References		
	Official reports	Academic papers	News analyses
Evolution	E.g. [74–82]	E.g. [32,52,58,61,83–98]	E.g. [1,5,7,10,31,69,70,99–103]
Evidences	E.g. [21,68,104–106]	E.g. [3,8,11,13–15,18,24,30,32,46,49,50,55,57,61,87,107–134]	E.g. [7,9,26,29,39,135–140]
Challenges	E.g. [4,37,78,82,141–147]	E.g. [3,42,43,46,52–55,58–60,64,86,91,93,99,107,108,114,120,121,125,148–177]	E.g. [5,10,31,40,69,101–103]

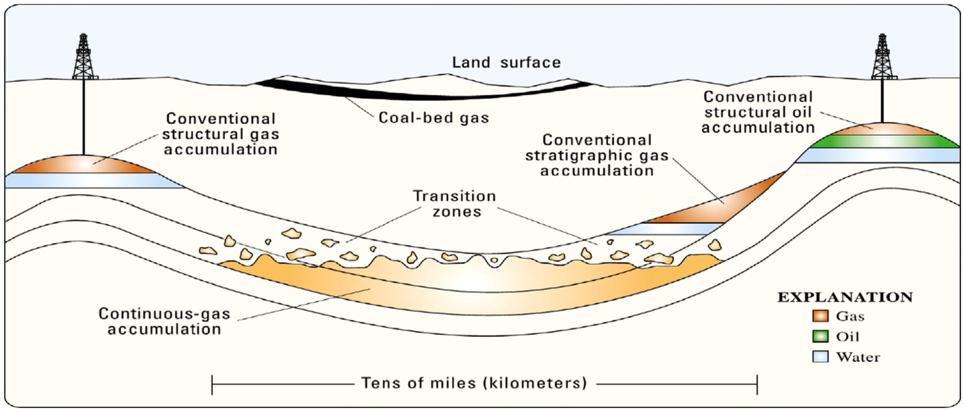

Fig. 1. Schematic geology of shale gas compared to other types of gas deposits.
Source: Ref. [185].

Table 2
Comparison the four types of unconventional gas.
Source: [184,186–188].

Types	Geological characteristics
Shale gas	Shale gas is in shale deposits, which are typically found in river deltas, lake deposits or floodplains. Shale is both the source and the reservoir for the natural gas. This can either be "free gas" which is trapped in the pores and fissures of the shale rocks, or adsorbed gas which is contained in surfaces of the rocks
Coal-bed methane	Coal-bed methane is produced from and stored in coal seams which are of extremely low permeability
Tight gas	Unlike shale gas or coal-bed methane, tight gas is formed outside the rock formations where it has migrated over millions of years into extremely impermeable hard rock or sandstone or limestone formations which are unusually non-porous
Methane hydrates	Methane hydrates is a crystalline combination of methane and water formed at low temperatures under high pressure in the permafrost and under the oceans

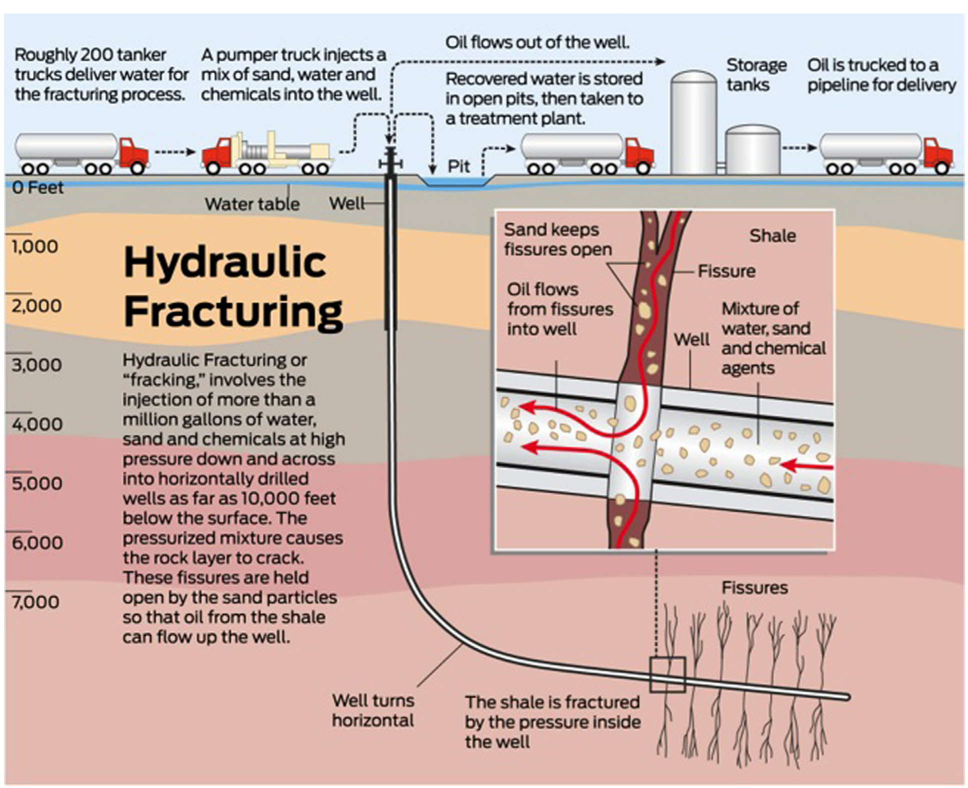

Fig. 2. Diagram of a typical hydraulic fracturing in Marcellus Shale.
Source: Refs. [193,194].

1.2. The research gap of US shale gas revolution

A series of reports, papers, and news analyses have been released to present the evolution of shale gas revolution, analyze key evidences of revolution in US, and discuss the possible environmental challenges due to the extraction of shale gas (Table 1). However, there is lack of an overview of the evolution, evidences and challenge of US shale gas for the broader community. The article aims to provide a broad overview of the evolution of shale gas in the US, and giving an insight into the environmental challenges shale gas has faced. To this end, the paper is organized as follows: Section 2 provides an overview of the evolution of US shale gas industry; Section 3 investigates the key consequences of the US shale gas revolution; Section 4 discusses the environmental concerns attributed to the extraction of shale gas. The recommendations and outlook are provided in Section 5.

2. The evolution of shale gas in US

2.1. Background information

2.1.1. What is the shale gas?

(i) What is unconventional natural gas?
The definition of unconventional natural gas is a function of many geological and economic factors [178–182]. In the broadest sense, natural gas is classified as unconventional gas if it is situated in rocks formation with a permeability of less than 1 millidarcy, which makes the gas difficult to flow. On the contrary, natural gas deposit can be defined as conventional gas if it is contained in rocks (often limestone or sandstone) with a permeability of more than 1000 microdarcy, which have interconnected spaces that allow the gas to flow freely in the rock and to well boreholes [178,179].
It should be pointed out that choosing a single value of permeability to define "unconventional gas" is of limited significance. In deep, high-pressure, thick reservoirs, commercial completions can be achieved when the formation permeability is in the microdarcy range [94]. In shallow, low-pressure, thin reservoirs, permeabilities of several millidarcies might be required to produce the gas at economic flow rates, even after a successful fracture treatment [180]. Another determining factor of what unconventional natural gas is an economic one. The updated economic definition of unconventional gas is as "natural gas that cannot be produced at economic flow rates nor in economic volumes of natural gas unless the well is stimulated by a large hydraulic fracture treatment, a horizontal wellbore, or by using multilateral wellbores or some other technique to expose more of the reservoir to the wellbore" [180]. However, this definition may be revised in the future in the event of technological advances.

(ii) What is shale gas?
Essentially, there are four main types of unconventional natural gas. These are shale gas, coal-bed methane, tight gas,

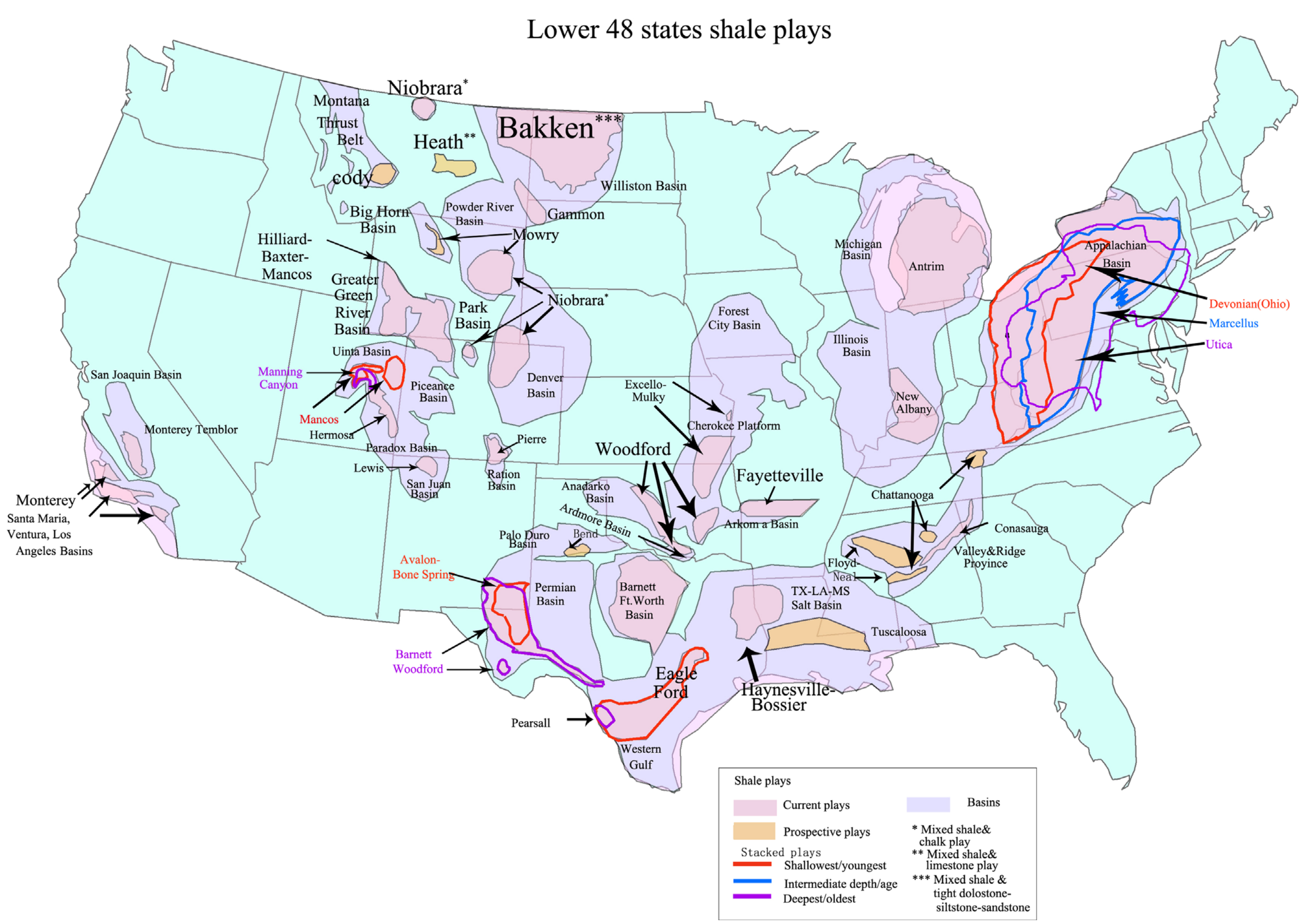

Fig. 3. Map of United States shale gas plays.
Source: Ref. [78].

and gas hydrates [180,181,183,184]. A geological comparison of these four types is shown in Fig. 1 and Table 2, so as to understand what shale gas is.

2.1.2. What is hydraulic fracturing?

Hydraulic fracturing is a method used to increase the flowrate of oil and gas wells (Fig. 2). The process of hydraulic fracturing begins with building the necessary site infrastructure including well construction. Production wells are drilled to a depth between 8000 and 10,000 ft [189,190] and may have horizontal or directional sections. A hydraulic fracture is formed by pumping the fracturing fluid into the wellbore at a rate sufficient to increase pressure downhole to exceed that of the fracture gradient/pressure gradient of the surrounding rock. The fracturing fluids, commonly made up of water (over 90%) and chemical additives, are pumped into a geologic formation at high pressure during hydraulic fracturing [108,191]. After the fractures are created, operators typically try to maintain fracture width, by introducing into the injected fluid a proppant that prevent the fractures from closing when the injection is stopped and the pressure of the fluid is reduced. The propped fracture is permeable enough to allow the flow of formation fluids to the well. Formation fluids such as oil, gas, and geothermal energy were introduced to the formation during completion of the well during fracturing [20]. After fracturing is completed, the internal pressure of the geologic formation causes the injected fracturing fluids to rise to the surface where it may be stored in tanks or pits prior to disposal or recycling. Recovered fracturing fluids are referred to as flowback or produced water. Disposal options for flowback or produced water include discharge into surface water or underground injection [189,190,192].

2.1.3. How much is the estimated shale gas resources in the US?

In June 2012, the estimated technically recoverable resource of shale gas for the US is 482 trillion cubic feet, substantially below the estimate of 827 trillion cubic feet in Annual Energy Outlook (*AEO*) 2011 [78,143]. This decline largely reflects a decrease in the estimate for the Marcellus shale, from 410 trillion cubic feet to 141 trillion cubic feet. Both EIA and USGS have recently made significant revisions to their technically recoverable resource estimates for the Marcellus shale. Drilling in the Marcellus Shale Play accelerated rapidly in 2010 and 2011, so that there is far more information available today than a year ago. Indeed, the daily rate of Marcellus production doubled during 2011 alone. Using data through 2010, USGS updated its technically recoverable resource estimate for the Marcellus to 84 trillion cubic feet, with a 90-percent confidence range from 43 to 144 trillion cubic feet – a substantial increase over the previous USGS estimate of 2 trillion cubic feet dating from 2002. For *AEO2012*, EIA uses more recent drilling and production data available through 2011 and excludes production experience from the pre-shale era (before 2008). EIA's technically recoverable resource estimate for the entire Northeast also includes technically recoverable resource of 16 trillion cubic feet for the Utica shale, which underlies the Marcellus and is still relatively little explored [144]. The largest concentrations of shale gas are contained in the Northeast region which contains the Marcellus Shale and the Gulf Coast region containing the Haynesville Shale (Fig. 3).

2.2. The evolution of shale gas industry in US

2.2.1. Oil price is used as an indicator

As we know, the restricted access to conventional fossil fuels in a global sense and increased pressure policy pressure on carbon reduction are driving factors behind alternative fuels [36,195,196]. The US has not committed itself to a reduction of carbon emission, as its government did not ratify the Kyoto Protocol [122,197].

Table 3
Selected progress of the shale gas development in the US between 1821 and 1970s.
Sources: [79,118,206]

Time	Brief introduction
1821	In 1821, the first well was drilled in the Devonian Dunkirk Shale in Chautauqua County, New York. The natural gas was used to illuminate the town of Fredonia
1859	The Drake Well was developed in 1859 at Cherrytree Township, Venango County in the northwestern Pennsylvania. The Drake Well demonstrates that oil can be produced in large volumes. Hence, the Drake Well is viewed as one of the most important oil well ever drilled
1860s–1930s	(i) Shale-gas development spread westward along the southern shore of Lake Erie and reached northeastern Ohio in the 1870s. In 1863, gas was discovered in the western Kentucky part of the Illinois basin (ii) By the 1920s, drilling for shale gas had progressed into West Virginia, Kentucky, and Indiana (iii) By 1926, the Devonian shale gas fields of eastern Kentucky and West Virginia comprised the largest known gas occurrences in the world
Late 1940s	Hydraulic fracturing first used to stimulate oil and gas wells. The first hydraulic fracturing treatment was pumped in 1947 on a gas well operated by Pan American Petroleum Corporation in Grant County, Kansas

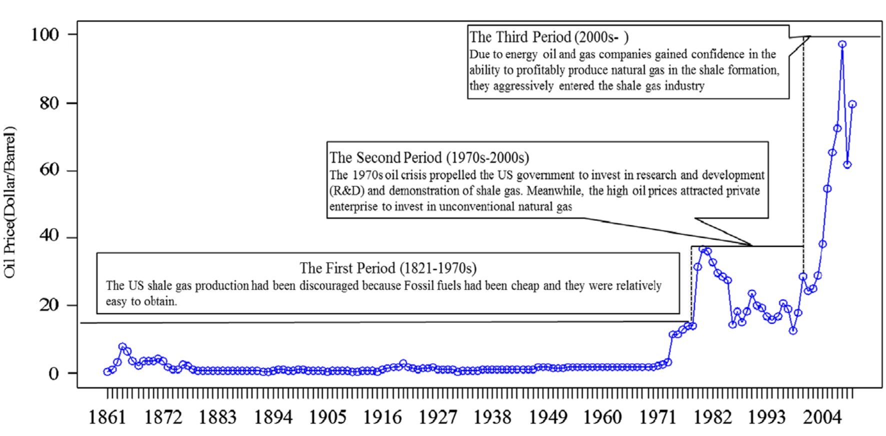

Fig. 4. The three period of shale gas development in the US based on oil price. Note: Oil prices 1861–1944 US average; 1945–1983 Arabian Light posted at Ras Tanura; 1984–2010 Brent dated. Oil prices
Source: Ref. [22].

Therefore, the main driving force behind alternative fuel in the US is the scarcity of conventional fossil fuels, although internal policy does acknowledge the need to address climate change [130,198–200].

Oil is a globally traded commodity. Traditional thought has held that commodity prices all correlate with oil [201,202]. The oil price can not only reflect the scarcity of fossil fuel, but can also adjust energy demand and supply [95,119]. Indeed, on one hand, consumers respond to high oil price by switching to alternative energy sources. On the other hand, high oil price encourages entrepreneurs to invest in the research and development of alternative fuels [203–205].

Oil price is used as an indicator in this paper to divide the evolution of shale gas development in the US. As shown in Fig. 4, the first period is before the 1970s oil crisis, the second period is from 1970s to 2000s, and the third period is after 2000s when the age of cheap oil has appeared to have ended.

2.2.2. The infant period (1821–1970s)

The first use of shale gas in the US can be traced back to 1821, when a shallow well drilled in the Devonian Dunkirk Shale in Chautauqua County, New York (Table 3). The natural gas was produced, transported and sold to local establishments in the town of Fredonia [118,156]. Following this discovery, hundreds of shallow shale wells were drilled along the Lake Erie shoreline and eventually several shale gas fields were established southeastward from the lake in the late 1800's [156]. However, shale gas production had been discouraged because much larger volumes natural gas could produce from conventional reservoirs as with the Drake Well developed in 1859 (see Table 3) [118]. These main stages in the shale gas industry from 1860 to 1970s were shale gas reservoirs discovered in the western Kentucky in 1863, in West Virginia in the 1920s, and hydraulic fracturing first used in the 1940s (Table 3).

2.2.3. The large demonstration period (1970s–2000s)

2.2.3.1. The supporting policies for large demonstration. The 1973 and 1979 oil crises had led the US to address energy shortages, and high price of oil. The 1970s oil crisis propelled the US government to invest in research and development (R&D) and demonstration of alternative energy, including natural gas from shale formations. Meanwhile, the high oil prices attracted private enterprise to invest in unconventional natural gas [205,207–210].

Before 1970s, deep shale gas, such as the Barnett Shale in Texas and Marcellus in Pennsylvania, has been known but believed to have extremely low permeability and thus were not considered economic [206,211,212]. In the late 1970s, the US Department of Energy (DOE) initiated the Eastern Gas Shale Project (EGSP) as a

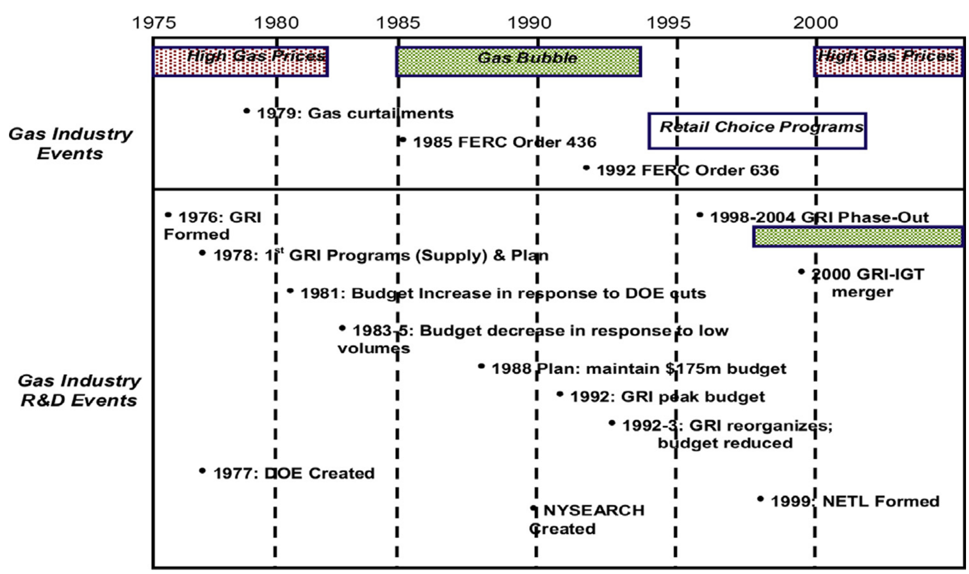

Fig. 5. A timeline of US official gas industry research institution.
Source: Ref. [152].

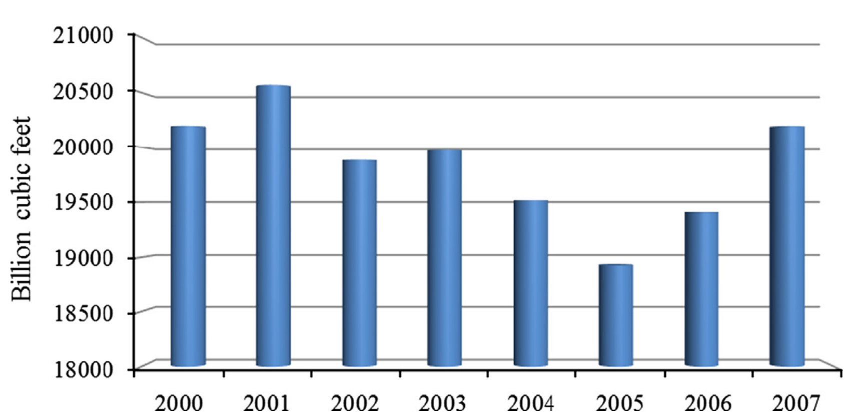

Fig. 6. US domestic natural gas production between 2000 and 2007.
Source: Ref. [228].

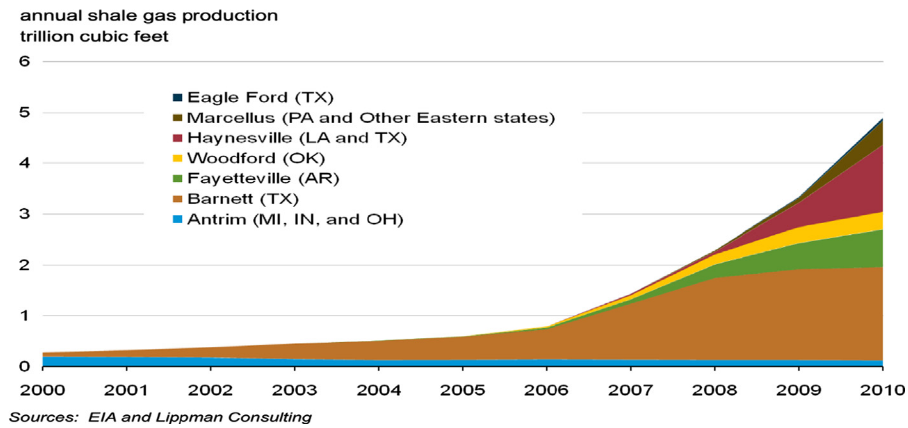

Fig. 7. U.S. shale gas production from 2000 to 2010.
Source: Ref. [229].

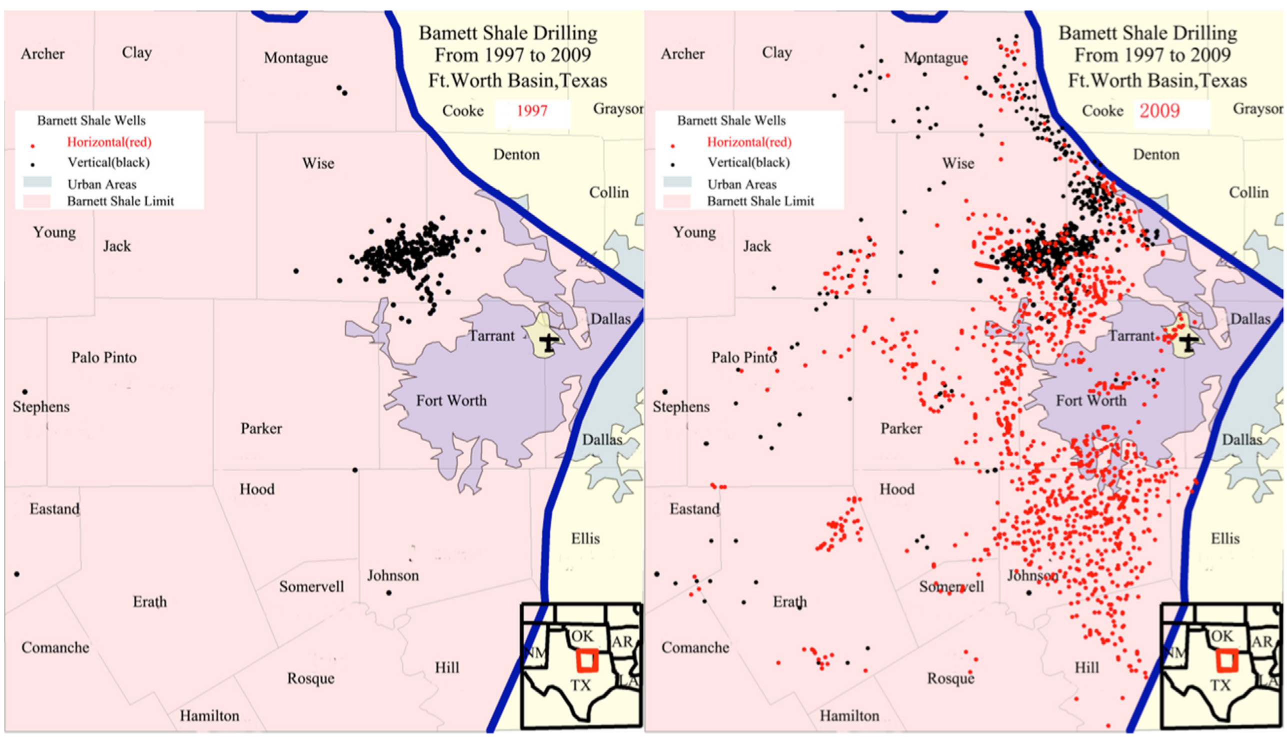

Fig. 8. A comparison of the numbers of shale gas well in 1997 and in 2009 in the Barnett Shale Play.
Source: Ref. [229].

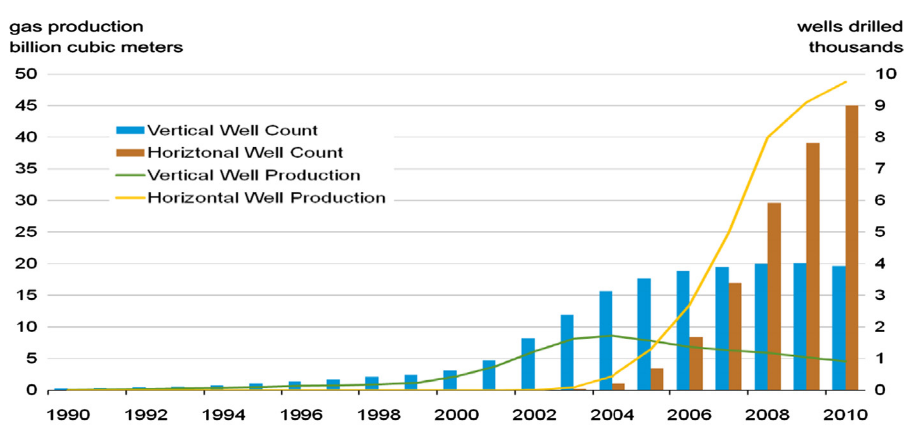

Fig. 9. The result has been rapid increases in production from the Barnett field.
Source: Ref. [229].

series of geological, geochemical, and petroleum engineering studies to evaluate the gas potential of, and to enhance gas production from the extensive Devonian and Mississippian organic-rich black shale within the Appalachian, Illinois, and Michigan basins in the eastern US [84,206,211–214].

In addition to providing R&D support, the Gas Research Institute (GRI) was established in 1977 [152]. The GRI was providing central organizations to manage the public research programs that were funded via mechanisms designed to pass R&D costs through to the end-customer. A few years later, the DOE was established and funding for energy R&D, in general, and in particular, supplemental gas supplies, were substantially increased. During the 1980s and early 1990s, GRI was expanded to include R&D programs addressing supply, transmission, distribution and end-use. In the late 1990s, the National Energy Technology Laboratory (NETL) was established. A consolidated research program led by NETL was initiated aimed primarily at preventing pipeline damage of the aging natural gas infrastructure in the US. In the same time period, GRI was reorganized to emphasize near-term industry impact. In 2000, GRI and the Institute of Gas Technology (IGT), which had been the R&D performing laboratory for the gas distribution industry, merged to form the Gas Technology Institute (GTI) (see Fig. 5) [152].

2.2.3.2. The pioneering companies of large scale demonstration. Meanwhile, some pioneering oil and gas companies had tried to combine larger fracture designs, rigorous reservoir characterization, horizontal drilling, and lower cost approaches to hydraulic fracturing to make the extraction shale gas economic [37,209,215]. The best-known pioneering company is the Mitchell Energy & Development Corp. The company went on to test various processes of hydraulic fracturing to exploit natural gas in the Barnett Shale formation in North Texas between 1981 and the early 1990s. Production from many of the 30 or so test wells fell short of covering operational costs. The company focused on the test results yielding the greatest returns. The engineers of this company analyzed and retested until eventually, the successful use of hydraulic fracturing to drill into shale formation for natural gas was completed [37,176,189,192,216–218]. The hydraulic fracturing techniques developed by the Mitchell Energy & Development Corp. changed the face of the oil and gas industry [37,120,189,216,219].

In a word, these efforts from government and private enterprise during this period contributed to the rapid growth in output of shale gas. The output of shale gas in the US increased more than seven-fold between 1979 and 2000 [74]

2.2.4. The industrial-scale period (since 2000)

Since 2000, three factors have contributed to increase energy companies' confidence in the ability to profitably produce natural gas in the rock shale formation. Above all, the drilling techniques are more advanced. In 2002, Devon Energy Corp. invested $3.5 billion in cash and stock to acquire Mitchell Energy & Development Corp. Devon Energy Corp added horizontal drilling to its repertoire to make shale gas wells even more productive. In the few short years since then, technology has continued to improve: drilling techniques have continued to advance, and horizontal drilling has been employed by many exploration and production companies in search of unconventional resources. The use of horizontal drilling in conjunction with hydraulic fracturing greatly expanded the ability of producers to

Table 4
Deliverability and storage capacity at the US LNG import terminals (2006 and 2008).
Source: [76].

LNG terminal	Deliverability Mcf/day (year 2006)	Deliverability Mcf/day (year 2008)	Storage capacity Bcf (year 2008)
Onshore			
Existing			
Cove Point, MD	1000	1800	14.5
Everett, MA	725	725	3.5
Elba Island, GA	1200	1200	7.3
Lake Charles, LA	1800	1800	9.2
New			
Freeport LNG	0	1500	6.9
Sabine Pass	0	2600	10.2
Cameron LNG	0	1500	10.2
Onshore total	4725	11,125	61.8
Offshore			
Gulf Gateway	500	500	0

Mcf=Million Cubic Feet; Bcf=Billion Cubic Feet.

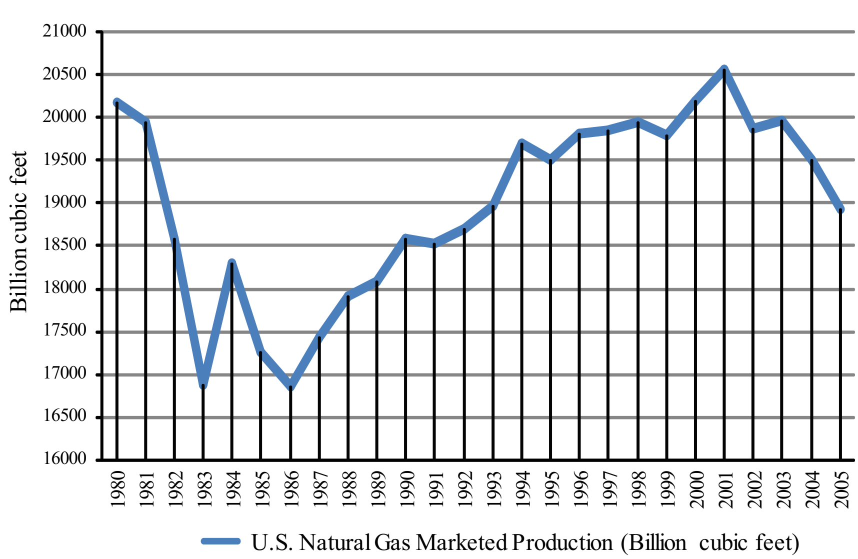

Fig. 10. US natural gas production between 1980 and 2005.
Source: Ref. [228].

profitably produce natural gas from low permeability shale formations [37,97,120,208,216,220–222].

In addition, the recent rise in oil and gas prices since 2003 made shale gas more economically attractive than ever before [223,224]. From the mid-1980s to 2003, the price of crude oil was generally under $25/barrel [22]. The crude oil price rose above $30/barrel in 2003, reached $60/barrel in 2005, exceed $75/barrel in 2006, reached nearly $100/barrel in 2007, and peaked over $140/barrel in 2008 [225,226].

Finally, the prospect of falling domestic conventional gas production since 2000 triggered expectations of higher US gas price inflation in. As shown in Fig. 6, US gas production was in slow but steady decline in the early 2000s. In the early 2000s, it was expected that US natural gas prices would rise in response to the resulting tight market [5,24,227].

Due to growing confidence in their ability to profitably produce natural gas in shale formations, the upstream oil and gas companies aggressively entered the shale gas business. Drilling for gas has increased sharply by the independent energy companies such as Devon Energy, Goodrich Petroleum and XTO Energy. This can be shown by the development of the Barnett Shale Play, the largest producible reserves of any onshore natural gas field in the US (Fig. 7) [44,208,227]. From 1997 to 2009, more than 13,500 gas wells have been drilled in the Barnett Shale Play (Fig. 8). Naturally, the output of natural gas from the Barnett Shale Play increased sharply (see Fig. 9). In 2004, gas production from the Barnett Shale Play overtook the level of shallow shale gas production from historic shale plays such as the Appalachian Ohio Shale and Michigan Basin Antrim plays [211].

Inspired by the success of Barnett Shale Play, oil and gas companies rapidly entered other shale formation, including the Fayetteville Haynesville, Marcellus, Woodford, Eagle Ford and other shale plays [37]. The proliferation of activity in these new plays has increased shale gas production in the US from 1.0 trillion cubic feet in 2006 to 4.87 trillion cubic feet, or 23% of total US natural gas production in 2010 [4].

3. Main evidences of US shale gas revolution

As Dr. Daniel Yergin claims, "the rapidity and sheer scale of the shale breakthrough – and its effects on markets – qualified it as the most significant innovation in energy so far since the start of the 21st century." Natural gas from rock shale formation has made a huge difference in the US outlook, such as energy independence, carbon reduction, lowering gas price, and stimulating economic growth and job creation [2,6,7,17,18,99,110,135,161,230].

3.1. Energy independence

Energy independence has been pursued by the US government since 1973, when the oil producing nations in Middle East imposed an oil embargo on the US [128,231–234]. However, the

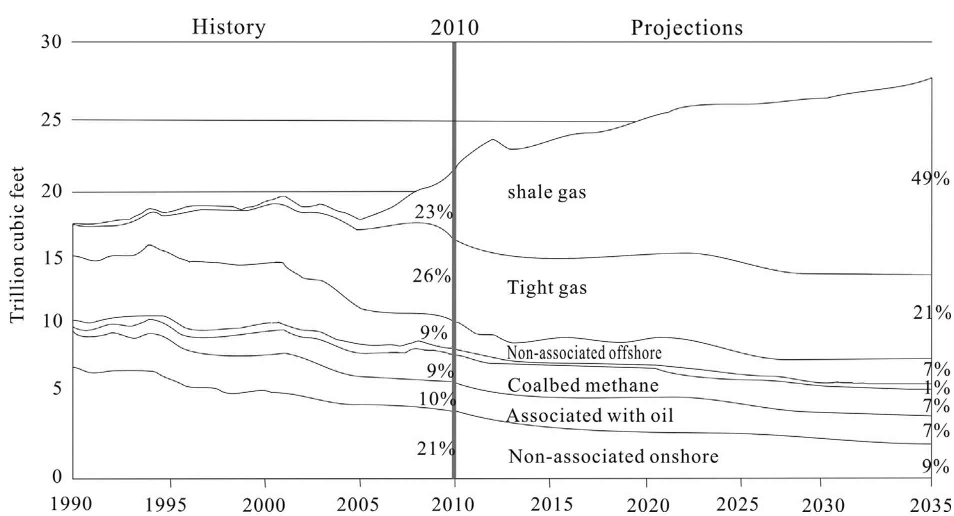

Fig. 11. U.S. natural gas production from 1990 to 2035.
Source: Ref. [143].

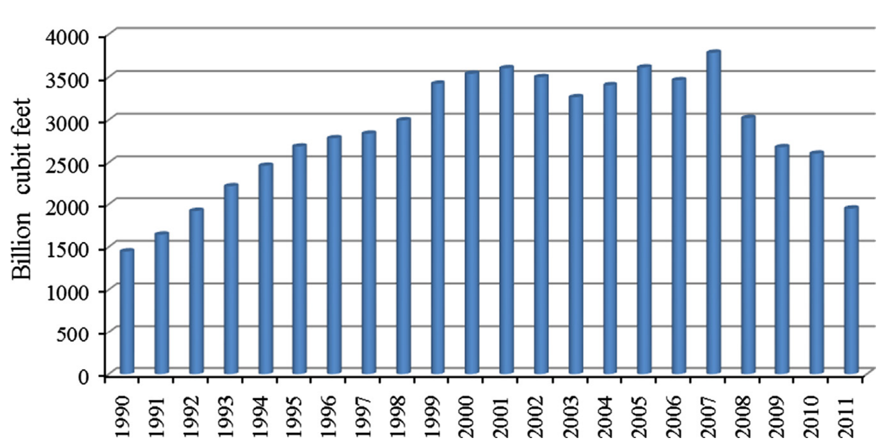

Fig. 12. US natural gas import and export between 1990 and 2010.
Source: Ref. [80].

"peak oil theory" indicated that the US would become not less but more energy-dependent [232,235]. The peak oil theory has it that the rate of oil production tends to follow a bell-shaped curve for any given geographic area (from an individual oil-producing region to a nation), which means that production would pass a maximum production and thereafter would decline [235]. Indeed, as US conventional oil production peaked in the 1970s, the US imported oil rose from one-third of consumption in the 1970s to about half in 2000s [236].

US conventional natural gas production also peaked in the beginning of 21st century (Fig. 10). The supply-side solution appeared to lie in the development of liquefied natural gas (LNG) projects in the Middle East, Africa, Australia and Russia for importation to the US market [76,112]. In the *Short-Term Energy Outlook Supplement: U.S. LNG Imports – The Next Wave* released in 2007, the EIA expected that the US would need a continued high level of LNG imports to meet gas demand [76]. In 2007 or so, US LNG import terminals were expected to expand or had a plan for expansion [237]. As of December 2006, there were four operating onshore LNG import terminals in US with a combined peak send out capacity of 4725 million cubic feet (Mcf)/d. There were plans for another three LNG import terminals with an expected total combined peak send out capacity of more than 5600 Mcf/d by the end of 2008 [76] (Table 4).

Shale gas had made a difference, contributing to make US contemplate self-sufficiency in natural gas. Shale gas production in the US grew from 0.39 trillion cubic feet in 2000, or less than 1% of US dry gas production, to 4.87 trillion cubic feet in 2010, or 23% of US dry gas production [143] (see Fig. 11). The shale gas production boom reduced US natural gas imports in 2011 to levels not seen since 1994 [4] (see Fig. 12).

In the future, shale gas will be the main driver of the US natural gas independence. In the *AEO2011* and *AEO 2012*, US domestic shale gas production is projected to increase to 13.6 trillion cubic

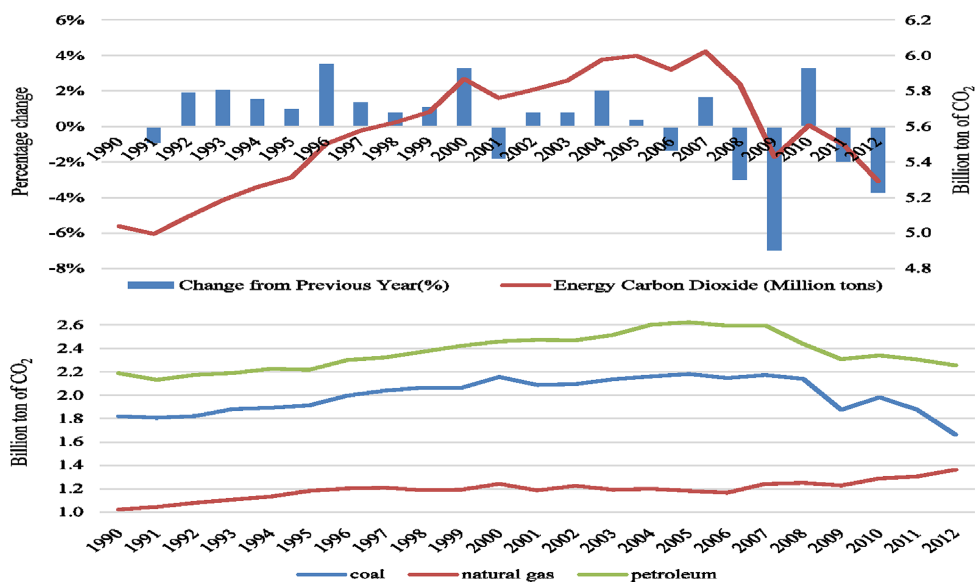

Fig. 13. (up) US energy-related carbon dioxide emission from 1990 to 2012, (down) US energy-related carbon dioxide emission by major source.
Source: Ref. [241].

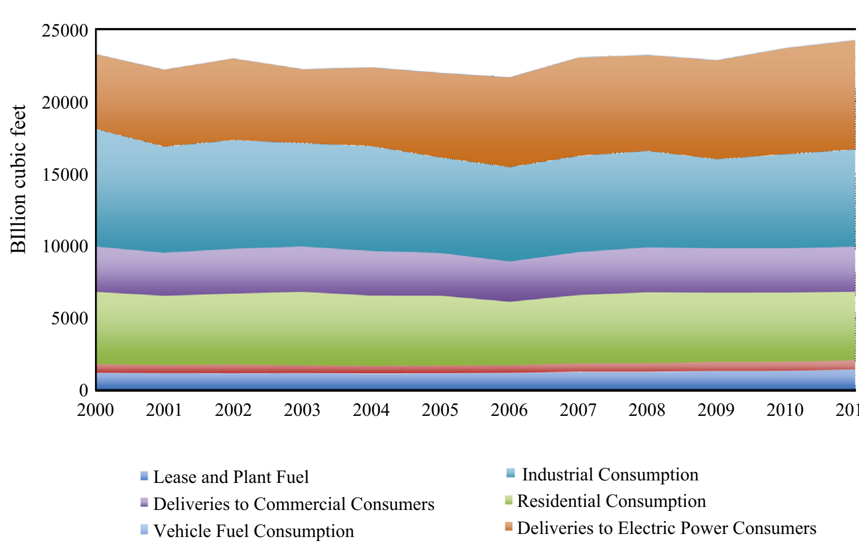

Fig. 14. US natural gas consumption by source between 2000 and 2010.
Source: Ref. [252].

feet in 2035, representing 49% of the total US gas production (Fig. 11). Natural gas consumption is also projected to grow however it is expected that production will exceed consumption. The resulting gap will facilitate greater exports of gas [4,143]. In the *AEO2012* reference case, the US will become a net exporter of LNG starting in 2016 and an overall net exporter of natural gas in 2021. The US LNG exports are assumed to start with a capacity of 1.1 billion cubic feet per day in 2016 and expected to increase by an additional 1.1 billion cubic feet per day in 2019 [143].

3.2. Carbon reduction

The Kyoto Protocol was established with the goal of achieving the "stabilization of greenhouse gas concentrations" in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system under the Kyoto Protocol. 37 Annex I countries (industrialized countries) commit themselves to binding targets for greenhouse gas emissions, whereas non-Annex I countries (emerging countries) are not subjected to emission reduction commitments [233,238]. The US was the only remaining signatory not to have ratified the Kyoto Protocol [122,197]. However, both reports from the IEA and the EIA show that carbon emissions from fossil-fuel combustion in the US has decreased sharply in recent years. Furthermore, carbon emission from fossil-fuel combustion in the US is most likely to be back to 1990 levels by 2012.

3.2.1. US carbon reduction of IEA version

According to the IEA report released in May 2012, fossil fuel combustion carbon dioxide emissions in the US have fallen by 430 million ton (7.7%) from 2006 to 2011, the largest reduction of all countries or regions surveyed [25]. Compared to this, the global carbon dioxide emission from fossil-fuel combustion reached a record high of 31.6gigatons (Gt) in 2011. What caused the carbon emission reduction in US? The answer is substantial shift from coal to natural gas in power generation and lower oil use in the transport sector (linked to efficiency improvements, higher oil prices and the economic downturn which has cut vehicle miles traveled) [25,239,240]. Dr. Fatih Birol, the Chief Economist of the IEA, says: "The replacement of coal by shale gas is a key factor and what happened in the US could very well happen in China and other countries and could definitely help in reducing CO_2 emissions" [101].

3.2.2. The US energy-related CO_2 emissions fall to the lowest level since 1994

According to EIA's Monthly Energy Review released in April 2013, about 5.3 billion metric ton of CO_2 were emitted from US coal, natural gas, and oil consumption in 2012, a 3.7% decline relative to 2011 and the lowest in the lowest since 1994 (Fig. 13). Shifted power generation from the most carbon-intensive fossil fuel (coal) to the least carbon-intensive fossil fuel (natural gas) is the primary reason for reduction of carbon emission from fossil energy combustion in US [241]

In 2012, lower natural gas prices resulted in reduced levels of coal generation, and increased natural gas generation gas-fired power plants have increased from 25% of US total generating electricity in 2011 to 30% of 2012. Coal has fallen to 37% of the US electricity generated in the first quarter of 2012, from 42% a year ago. For the first time since the 1970s, coal's share of energy production has fallen to 37%. Gas is a less carbon-intensive fuel for power generation [242].

For US carbon emissions from fossil fuel energy combustion, fuel switching to gas is back to the future. The 2012 emissions is

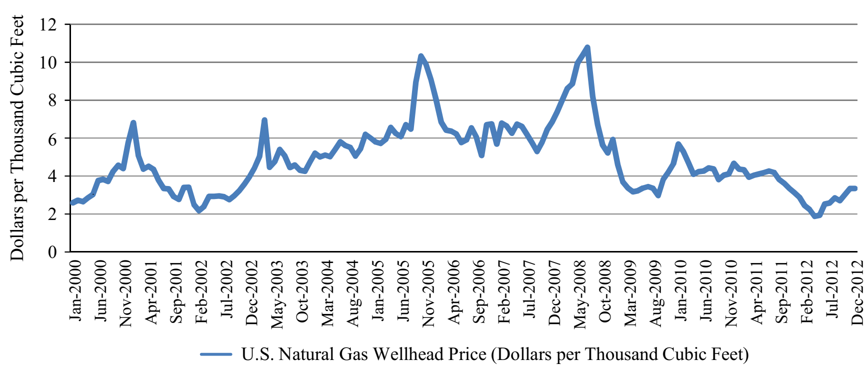

Fig. 15. Monthly US dry natural gas production and Henry Hub natural gas spot price between January 2000 and May 2012.
Source: Ref. [251].

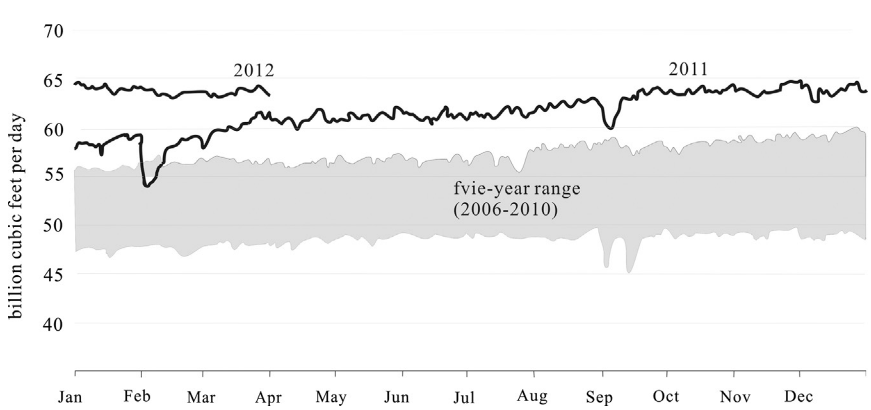

Fig. 16. US daily dry natural gas production.
Source: Ref. [81].

nearly to the 1990 level of 5039 million ton [243]. The 1990 level of carbon emissions is an important measuring stick, as it is often used as a critical data point for judging progress in reducing a nation's carbon emissions. It was thought impossible to slash US carbon emissions back to 1990 levels by 2012, because no real effort by the US government is addressed on global warming and America has longstanding reputation as an energy hog. However, the shale gas revolution has made a reality many things recently thought impossible in the US carbon reduction.

3.3. *New era of cheap natural gas*

Due to burner tip competition between natural gas and oil products and the general similarity of their production technologies natural gas and crude oil prices have been historically closely related [132,158,244–246]. In the context of the co-integrating relationship between natural gas and crude oil prices [87,158,247], 'the end of cheap oil' [91,226,248] raises the question of whether the era of cheap natural gas in the US will end. Shale gas has made a difference. The shale gas boom has contributed to not only to the birth of a new era of cheap natural gas, but also the decoupling of US domestic natural gas price from crude oil price, which has a significant effect on the global gas pricing system.

3.3.1. *Domestic natural gas price hit a 10-years low*

On one hand, US demand for natural gas has been fairly flat for the last 10 years, regardless of price. The four major users of natural gas are (a) electric powergenerators, (b) industrial consumers, (c) commercial consumers and (d) residential customers. Of these four, only electrical power has been growing (Fig. 14). Even with very low prices in 2011, total natural gas consumption only rose by 2.2% in 2011 compared to 2010 (Fig. 14). On the other hand, the rapid growth in production of shale gas has contributed to continued growth in natural gas production (Fig. 11). The US natural gas pricing system is based on supply and demand [126,249]. If there is a mismatch between supply and demand, natural gas price will drop or rise in response [153]. Continued high production levels of natural gas and a near stagnation in demand (Figs. 11 and 14) have led US domestic natural gas price to fall since late 2005 [250,251] (Fig. 15).

In the first half of 2012, the US domestic natural gas price hit a 10-years low as a result of high production levels and slack demand. As shown in Fig. 16, after a long period of steady growth, US daily dry gas production growth leveled off during the first 3 months of 2012, averaging 63.8 billion cubic feet (Bcf)/d through March 31, a level almost 9% above the same period in 2011 [81]. Fig. 17 shows storage levels of US natural gas to be 2479 Bcf/d for the week ending March 30, more than 60% above the 5-year average for that week. Correspondingly, on March 31, the spot natural gas prices at the Henry Hub approached $2 per million BTU. On April 18, the natural gas spot price at Henry Hub was $1.87 per million BTU, which is a record low for the last decade – about where it was in 2002 [81].

The EIA projects that average annual wellhead prices for natural gas will remain below $5.1 per million BTU (2010 dollars) through 2023. The EIA's projected prices assume continued industry success in developing the nation's extensive shale gas resource. The resilience of drilling levels, despite low natural gas prices, is in part a result of high crude oil prices, which significantly improve the economics of natural gas plays that have high concentrations of crude oil, condensates, or natural gas liquids. After 2023, natural gas prices are assumed to generally increase as the numbers of tight gas and shale gas wells drilled increased to meet growing domestic demand for natural gas and offset declines in natural gas production from other sources. Natural gas prices rise as production gradually shifts to resources that are less productive and more expensive. Natural gas wellhead prices (in 2010 dollars) reach $6.61 to $6.64 per million BTU in 2035 [4,143]. Compared to the natural gas, the crude oil price is projected to remain high, approaching $120 per barrel, or $21 per million BTU (in year-2010 dollars) in 2035 in the IEA's New Policies Scenario [253]. According to these projections, the shale gas boom has contributed to a new era of cheap natural gas in the US.

3.3.2. *Potential for change in global natural gas pricing*

In the first half of 2012, the price of gas in the US is a 60% of that in western Europe and a 20% of that in Asia [254,255]. Some US energy companies, such as Houston-based Cheniere Energy and Freeport LNG Expansion, L.P. (Freeport LNG) are in the process of developing facilities to export natural gas [256]. A $10 billion Sabine Pass liquefaction plant planned by Cheniere Energy has been given its final approval by the federal energy regulator, clearing the way for construction to start at the site on the coast of Louisiana. This project is the first project to export LNG from the US in more than 40 years. Cheniere has already lined up four customers: BG Group of the UK, Gas Natural Fenosa of Spain, Kogas of Korea and Gail of India, to export a total of 16 million ton of LNG per year, roughly 89% of the plant's possible maximum capacity if all four trains are built [102]. In addition, on July 30, 2012, Freeport LNG announced that it had executed 20-year liquefaction tolling agreements with Osaka Gas Co., Ltd. and Chubu Electric Power Co., Inc. covering 100% of the liquefaction capacity of the first train of Freeport LNG's proposed natural gas liquefaction and LNG loading facility near Freeport, Texas. The initial 3-train facility will be capable of liquefying approximately 13.2 million ton per annum of natural gas. Freeport LNG expects that all three trains will be fully subscribed by the end of 2012 [100,257].

The US Energy Department has commissioned a study of the impact of exports on domestic energy use, output and prices before

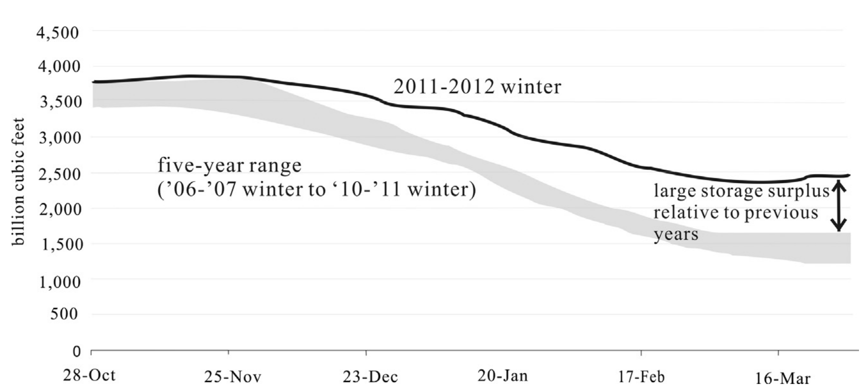

Fig. 17. US natural gas storage inventories.
Source: Ref. [81].

deciding on additional permit requests. Although the issue is whether the US would become a big natural gas exporter [102,136,143,254], the US export natural gas is a change of potentially huge proportions for global natural gas pricing system. For decades, global natural gas has been sold under 20-year contracts indexed to the price of oil. The global gas pricing system began in the 1970s when Japanese utilities started importing large volumes of LNG from countries under long-term contracts indexed to the so-called the Japan Customs-cleared Crude, or "Japanese Crude Cocktail" (JCC). JCC is the average price of customs-cleared crude oil imports into Japan as reported in customs statistics. South Korea and Taiwan followed suit, and the JCC link became standard for Asian buyers. There JCC is a commonly used index in long term LNG contracts in Japan, Korea and Taiwan [83,258]. Russian pipeline exports to Europe are similarly oil-indexed [85,258].

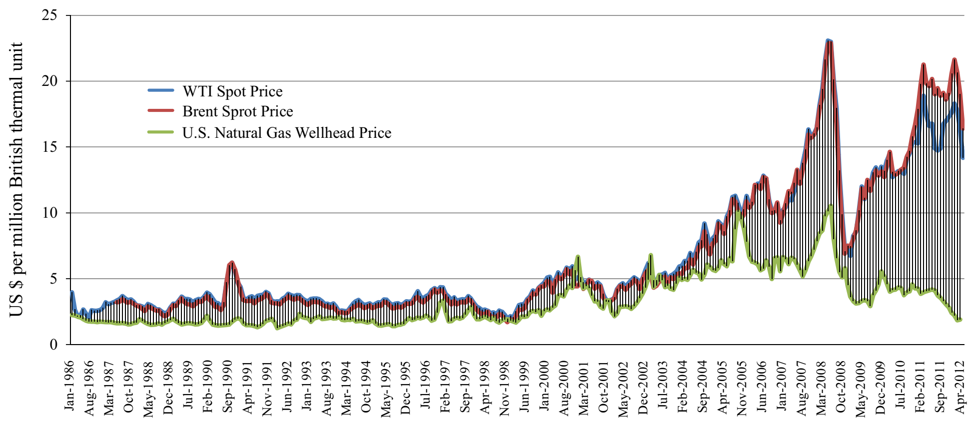

Fig. 18. The evolution of the US Wellhead gas price versus the Western Texas Intermediate crude spot oil price (WTI), and Brent spot price from January 1986 to May 2012. *Source*: Ref. [22, 251].

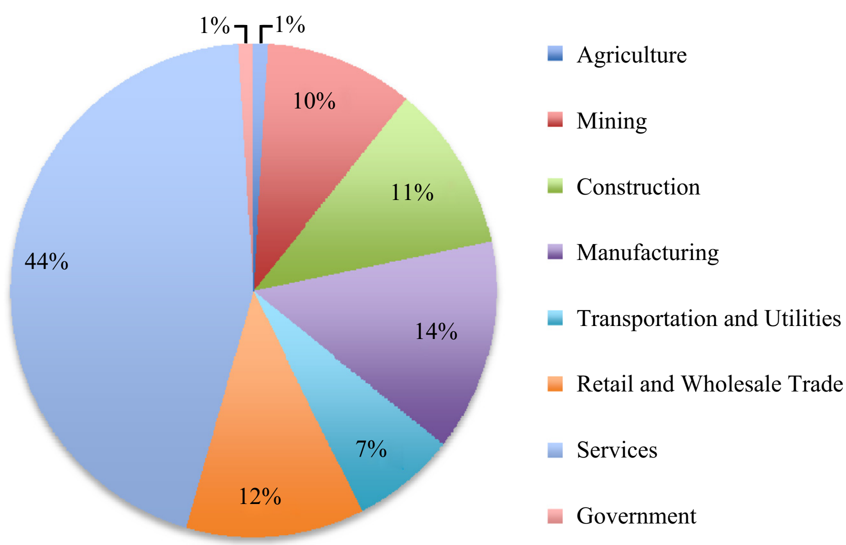

Fig. 19. US shale gas employment contribution in 2010. *Source*: Ref. [106].

Table 5
Summary of five studies about the impact of shale gas on local economy.

Researchers	Shale play	Main conclusion
CBER, Ref. [261]	Marcellus Shale in Arkansas	Shale gas extraction is estimated to increase gross revenues in the state of Arkansas by $2.6 billion and generate 9533 jobs in 2007
Considine et al., Ref. [259]	Marcellus Shale in western and northern Pennsylvania	The shale gas extraction industry is responsible for $2.263 billion in economic activity, the creation of 29,284 jobs, and the payment of $238.5 million in state and local taxes within the Pennsylvania in 2008
Considine et al., Ref. [262]	Marcellus Shale in western and northern Pennsylvania	(i) The shale gas industry is estimated to have contributed 44,098 jobs to the Pennsylvania economy and paid $389 million in state and local taxes in 2009. (ii). The economic impact of the shale gas industry is expected to $18.85 billion in value added, $1.87 billion in state and local taxes, and nearly 212,000 jobs by 2020
The Permanent Group, Ref. [263]	Barnett in Dallas/Ft. Worth Area	(i) The economic effects of Barnett Shale activity in 2006 was $6.1 billion in annual output and 60,820 jobs. (ii) The economic effects of Barnett Shale activity in 2007 was $8.4 billion in output and 83,823 positions. (iii) The economic effects of Barnett Shale activity in 2008 are even higher than in years past, with incremental output of $11.0 billion and 111,131 jobs
Scott, Ref. [264]	Haynesville in Louisiana	It was estimated that the extraction activity of these seven firms generated approximately $2.4 billion in new business sales within the state of Louisiana in 2008

Cheniere is doing it differently. Natural gas will be sold at a price indexed to Henry Hub, the main US gas benchmark. For the first time, the global natural gas trade is not based on indexed to the price of oil. As mentioned earlier, the Henry Hub natural gas spot price at about $2 per million BTU in the first half of 2012. After liquefaction, transport and other costs, LNG could be imported into Asia for less than $9 per million BTU – compared with a long-term contractual price of $17–19 per million BTU in Japan [10,100].

Therefore, the switch to Henry Hub pricing is a "paradigm shift". It is difficult to exaggerate the significance of this shift and its consequences for the pricing system of the global natural market (Fig. 18).

3.4. Job creation and industrial revival

3.4.1. Job creation

- Stimulating national economic growth and job creation
  The rapid growth in shale gas production is having profound economic impacts [93,106,149,259,260]. A report examining the economic impacts of unconventional gas activity suggests that the shale gas industry supported more than 600,000 jobs (Fig. 19) and by 2015 the total is likely to grow to nearly 870,000 and to more than 1.6 million by 2035 [106]. A key reason for the shale gas industry's profound economic impact is its high "employment multiplier" – the indirect and induced jobs created to support the industry. For every direct job created in the shale gas sector, more than three indirect and induced jobs are created, a rate higher than the financial and construction industries [106]. The shale gas contribution to the American gross domestic product (GDP) was more than $76.9 billion in 2010; in 2015 it will be $118.2 billion and will triple to $231.1 billion in 2035. Over the next 25 years, the shale gas industry will generate more than $933 billion in tax revenues for local, state and the federal governments. Savings from lower gas prices, as well as the associated lower prices for other consumer purchases, equate to an annual average addition of $926 in disposable income per household between 2012 and 2015, and increase to more than $2000 per household in 2035 on an annual basis [106].

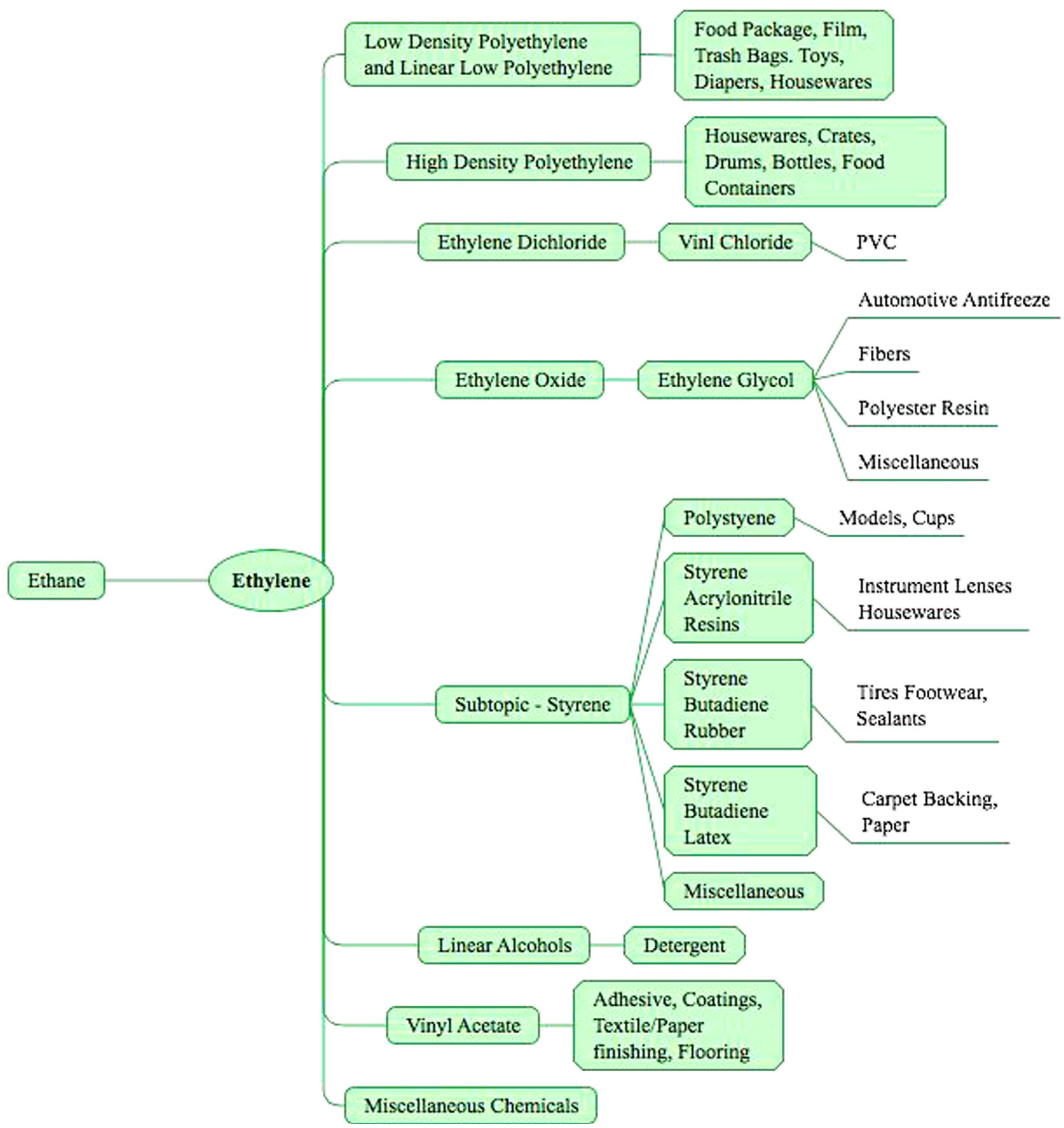

Fig. 20. A simplified ethylene supply chain from ethane feedstock through petrochemical.
Source: Ref. [266].

- Stimulating local economic growth and job creation
  Several reports estimate the impact of shale gas extraction on state and local job creation, economic growth. Table 5 summarizes the findings of five reports [133,259,261–264].

3.4.2. Industrial revival – a case study of chemical industry

Cheaper natural gas is giving the US chemical industry an advantage over foreign competitors that rely on an oil-based raw material instead of natural gas. As mentioned earlier, the shale gas

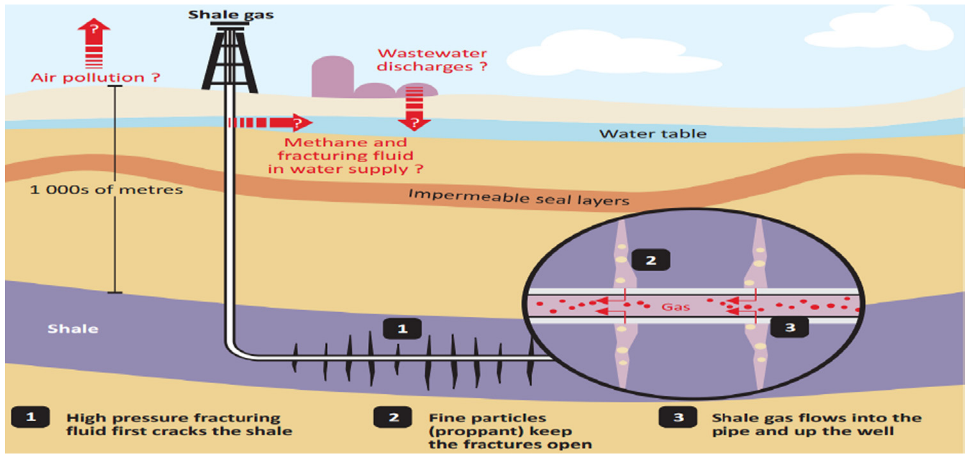

Fig. 21. Natural gas drilling practices raise environmental concerns.
Source: Ref. [68].

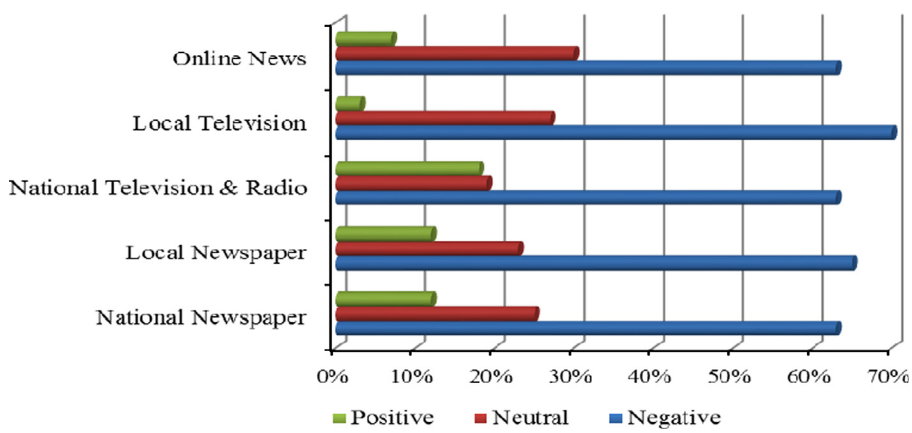

Fig. 22. Tone of media coverage.
Source: Ref. [269].

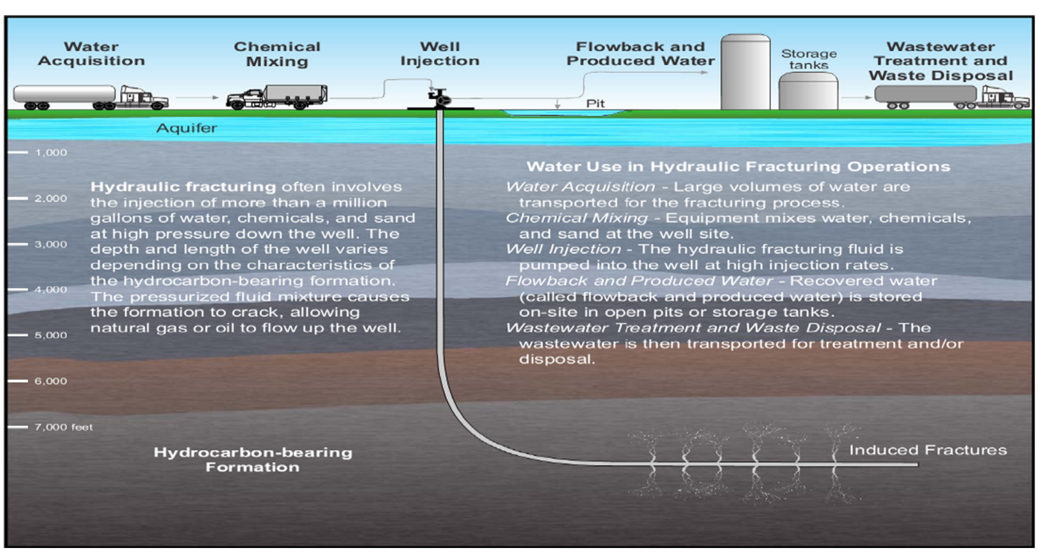

Fig. 23. The water lifecycle in hydraulic fracturing.
Source: Ref. [275].

boom has reduced the prices of natural gas as well as natural gas liquids (NGLs). One of these NGLs is ethane, which is used to manufacture ethylene, an organic compound with extensive applications in the chemical industry (Fig. 20). Ethylene can also be manufactured from oil-based naphtha [265]. The US chemicals use ethane, which is derived from NGLs, whereas international competitors rely on a more expensive oil-based raw material. Thus, the crucial factor of the US chemical industrial competitiveness is the difference between the price of US domestic natural gas and global crude oil. For example, with global oil prices at more than $80/barrel (about $14 per million BTU) and gas at $2/MBTU, the US chemistries industry now enjoys a 7–1 price advantage over its global rivals.

Chemical companies are taking advantage of cheap natural gas by expanding facilities and building new ones. In May 2012, new facilities and significant expansions – totaling $25 billion in capital investment took place [267]. One of the biggest investment was made by The Dow Chemical Company (DOW) to build an ethylene cracker and a new propylene production facility in Freeport, Texas. In fact, the $1.7 billion expansion is only part of a planned $4 billion expansion in Texas. The new facility in Freeport will not open until 2017, which indicates Dow's belief that cheap, abundant shale gas will be available in Texas for the foreseeable future. Such a project would have been unthinkable 5 or 10 years ago when natural gas prices were higher and gas supplies much tighter [76,112]. Dow's expansions will also bring jobs to a US economy that sorely needs them. In total, Dow expects to employ 4800 workers during construction of the project [103].

The underpinning for these chemical company projects is a steady supply of cheap natural gas. DOW would need to rise over $10 per million BTU while oil remained over $100/barrel in order for there to be problems with the return on investment of the project in Freeport. Of course, Dow does not expect natural gas prices, currently trading between $2 and $2.50 per million BTU in the US, to reach those heights for many years. Therefore, the shale gas boom is expected to keep ethane more cost-feasible, which in turn will give the United States chemical companies a sustainable international competitive advantage [103,268].

4. Environmental challenges

Naturally, accompanying the benefits of the shale gas extraction are environmental concerns (Fig. 21). Environmental impacts have not adequately been brought into discussions about natural gas extraction at earlier stages. With the continual expansion of natural gas production, the environmental issues associated with the shale gas have become increasingly controversial. Indeed, the potential environmental impacts have posed a significantly negative influence on public opposition, which is curbing and even halting the shale gas revolution in its tracks. The researchers of Energy Institute at The University of Texas researchers analyzed print, broadcast and online news media coverage of shale gas development in the Marcellus, Haynesville, and Barnett shale areas. They found the tone of media coverage been overwhelmingly negative in all forms of media coverage. Roughly two-thirds of the articles and stories examined were deemed negative, a finding that was consistent nationally and at local levels. These researchers also found that less than 20% of newspaper articles on hydraulic fracturing mention scientific research related to the issue. Similarly, only 25% of broadcast news stories examined made reference to scientific studies, and about 33% of online news coverage mentioned research on the issue [269] (Fig. 22). Here, we focus on four prominent environmental concerns surrounding hydraulic fracturing, i.e., water issues, greenhouse gas emissions, induced earthquake, and health concerns.

4.1. Water issues

Hydraulic fracturing involves the high-pressure injection of water and chemicals into the ground to split rock apart and release natural gas. Fig. 23 illustrates a typical drilling well in the Marcellus Shale. As shown in Fig. 24, a series of challenges have been posed for protecting water resources. Indeed, much of the opposition centers on water issues caused by extraction shale gas [41,49,50,64,65,92,125,157,167,170,222,270–274].

4.1.1. Large volume withdrawal water

The production of shale gas consumes a large volume of freshwater. The amount of water needed in the hydraulic fracturing process depends on the type of the shale gas and the fracturing operations, such as well depth and length, fracturing fluid properties, and fracture job design. As show in Table 6, 2–4 million gal of water are typically needed per horizontal well in shale gas production [275–277].

It was estimated that about 35,000 wells were fracked in 2006 in the US [134]. The annual national water requirement may range from 70 to 140 billion gal. This is equivalent to the amount of water consumed in a year by 5 million people [275]. Clearly, water consumption will grow with the increase in number of wells and shale gas production. For example, in the Barnett Shale Play (Fig. 8), the annual estimates of total water used by gas producers has increased from 2.6 billion gal in 2005 to 5.3 billion gal in 2007 and to 9.5 billion gal in 2010 [278].

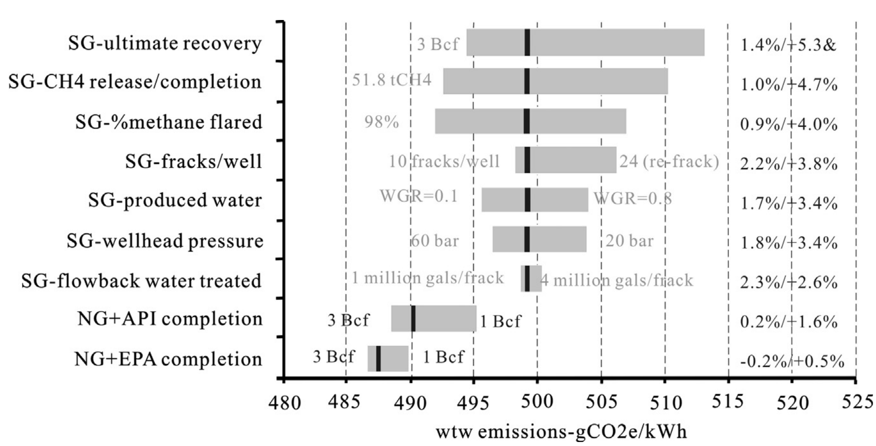

Fig. 24. Well-to-Wire emissions intensity to best/worst parameter settings changed one at a time about a 2 Bcf base case. Abbreviation: SG – Shale gas; NG – Natural gas; API – American Petroleum Institute; EPA – Environmental Protection Agency.
Source: Ref. [86].

One way to offset the large water requirements for hydraulic fracturing is to recycle the flowback or produced water in the fracturing process [279,280]. The produced water may be treated and reused by adding additional chemicals as well as fresh water to compose a new fracturing solution. There are, however, challenges associated with reusing flowback due to the high concentrations of total dissolved solids (TDS) and other dissolved constituents found in flowback [281]. Constituents such as specific cations (e.g., calcium, magnesium, iron, barium, and strontium) and anions (e.g., chloride, bicarbonate, phosphate, and sulfate) can interfere with hydraulic fracturing fluid performance by producing scale or by interfering with chemical additives in the fluids [282].

Certainly, such large volume water, high rate of withdrawals from local surface or ground water sources has a significant impact on local water system. However, so far, it is not clear how the large volume water withdrawals impact the local water system [113,283–285].

4.1.2. Potential for water contamination

The production of shale gas without good practices can contaminate the marine environment [41,49,50,65,92,124,129,137,177,270,286]. As mentioned earlier, chemicals are used throughout operations to reach and release natural gas from shale rock formation. Table 7 summarizes purposes of use of different chemical groups used in hydraulic fracturing [64]. Although some of the chemicals used are generally harmless [287,288], many of them are toxic and known carcinogens [151]. The 2011 US House of Representatives investigative report on the chemicals used in hydraulic fracturing states that out of 2500 hydraulic fracturing products, more than 650 are known or possible human carcinogens [271]. Presence of these genotoxic and carcinogenic chemicals in the aquatic environment has attracted regulatory attention in different parts of the world, including EU [173] as this could lead to short- and long-term survival of natural biota as well as having detrimental impact on human health [174,175].

Chemicals make up 0.5–2.0% of what is found in fluids of hydraulic fracturing – a small percentage of the total that can nevertheless add up to hundreds of thousands of gallons injected directly into the ground [46,108]. For example, a 4 million gal fracturing operation would use from 80 to 330 ton of chemicals [191]. However, a small quantity of chemicals used in fracking might be capable of contaminating millions of gallons of water. For example, benzene present in the petroleum-based products is a known human carcinogen and toxic in water at levels greater than 5 ppb (or 0.005 ppm) [162]. Therefore, these hydraulic fracturing fluids containing chemicals should be deemed to be "hazardous wastes" [146]. It is unconscionable that these hydraulic fracturing fluids are allowed to be injected directly into underground sources of drinking water, even if these chemicals are diluted [289].

In addition, flowback or "produced" water from fracturing fluid might contaminate surface waters [46]. It has been reported that a single well hydrofracturing in the Marcellus Shale may require 1–5 million gal of fracturing fluid, of which between 25% and 100% may be returned to the surface as flowback or "produced" water which might contaminate surface water. In addition to chemical additives, flowback water from Marcellus hydrofracturing typically contains high levels of TDS (ranging from 70,000 to 250,000 mg/L) hydrocarbons, and heavy metals. The presence of these constituents precludes untreated re-use or direct discharge onto land or into receiving streams, as they may adversely impact human health and environmental quality [146]. Conventional treatment processes, such as reverse osmosis and distillation, are not likely to be utilized due to their high capital costs and energy requirements [125]. Disposal by dilution into Public Owned Treatment Works (POTWs), the common method to date for handling Marcellus flowback water in Pennsylvania, is not sustainable either, as transportation costs are extremely high, and POTWs are limited as to how much water they can accept and treat. For example, in response to high TDS levels measured in the Monongahela River in the fall of 2008, the Pennsylvania Department of Environmental Protection ordered a restriction on the amount of flowback disposal to POTWs in the basin [290].

Finally, the principal component in shale gas, methane (CH_4) also can contaminate water [41,46,92,169]. Shale gas is typically comprised of over 90% methane [291] which can contaminate active drilling sites [41]. The US Department of the Interior recommends that immediate action should be taken to ventilate the well head when dissolved methane is present in water in concentrations greater than 28 milligrams (mg) per liter. At a

Table 6
Comparison of estimate water needs for hydraulic fracturing of horizontal wells in different shale plays.
Source: [275–277].

Shale play	Formation depth (ft)	Porosity (%)	Fracturing water (million gal/well)
Barnett	6500–8500	4–5	2.3
Fayetteville	1000–7000	2–8	2.9
Haynesville	10,500–13500	8–9	2.7
Marcellus	4000–8500	10	3.8

Table 7
Functional categories of hydraulic fracturing chemicals.
Source: [64].

Chemicals	Function
Acids	To achieve greater injection ability or penetration and later to dissolve minerals and clays to reduce clogging, allowing gas to flow to the surface
Biocides	To prevent bacteria that can produce acids that erode pipes and fittings and break down gellants that ensure that fluid viscosity and proppant transport are maintained
Breakers	To allow the breakdown of gellants used to carry the proppant, added near the end of the fracking sequence to enhance flowback
Clay stabilizers	To create a fluid barrier to prevent mobilization of clays, which can plug fractures
Corrosion inhibitors	To reduce the potential for rusting in pipes and casings
Crosslinkers	To thicken fluids often with metallic salts in order to increase viscosity and proppant transport
Defoamers	To reduce foaming after it is no longer needed in order to lower surface tension and allow trapped gas to escape
Foamers	To increase carrying-capacity while transporting proppants and decreasing the overall volume of fluid needed
Friction reducers	To make water slick and minimize the friction created under high pressure and to increase the rate and efficiency of moving the fracking fluid
Gellants	To increase viscosity and suspend sand during proppant transport
pH control	To maintain the pH at various stages using buffers to ensure maximum effectiveness of various additives
Proppants	To hold fissures open, allowing gas to flow out of the cracked formation, usually composed of sand and occasionally glass beads
Scale control	To prevent build up of mineral scale that can block fluid and gas passage through the pipes
Surfactants	To decrease liquid surface tension and improve fluid passage through pipes in either direction

concentration of more than 10 mg/L, occupants in the surrounding area should be warned, ignition sources should be removed from the areas, and remediation should be performed to reduce the methane concentration to less than 10 mg/L [292]. The average methane level from residential wells near drilling sites – 19.2 mg/L – was within the defined action level of > 10 mg/L but < 28 mg/L recommended for hazard mitigation by the US Department of the Interior. The maximum value of 64 mg/L constituted a potential explosion hazard [41].

4.2. Is shale gas good for climate change?

Based on the IPCC reports [293,294], the general consensus is that natural gas emits about half as much carbon as coal when used in efficient power plants. The official reports of carbon emission from fossil fuel combustion, such as IEA (e.g. [25,104]), EIA (e.g. [77]) and US EPA (e.g. [295]) are based on this consensus. In addition, the consensus are also adopted by the academic research papers about carbon emission (e.g, [296–299]).

However, if based on “carbon footprint” (life cycle greenhouse gas emission) [165,172], the effects of shale gas on climate change have become more complex and controversial, partly because of uncertainty about the extent of methane leaks [58,90,154,163,164,300,301]. Methane is a very powerful greenhouse gas, although it stays only one tenth period compared to carbon dioxide in the atmosphere. Methane has a global warming potential (GWP) that is 72-fold greater than carbon dioxide when viewed over a 20-year period and 33-fold greater when viewed over a 100-year period [147]. However, if considering the direct and indirect radioactive effects of aerosol responses, GWP of methane is 79 and 105 over a 20-year period [302]. Partly due to different estimation of full life-cycle methane emission from shale gas (Table 8), recent studies [43,57,58,60,61,86,89,115,148,154,163,164,273,303,304] have come to complex and conflicting conclusions whether the greenhouse gas footprint of shale gas would slow the climate change compared to coal and oil. The main contradictory conclusions are summarized in Table 8.

Table 8
Comparison of published estimates for full life-cycle methane emissions from conventional gas and shale gas.
Source: [57,164].

Researchers	Conventional gas (gC/MJ^{-1})	Shale gas (gC/MJ^{-1})
Howarth et al [163]	0.26–0.96	0.55–1.2
EPA [72]	0.38	0.60^{+}
Jiang et al. [43]	N/A	0.30
Fulton et al. [303]	0.38	N/A
Skone et al. [304]	0.27	0.37
Burnham et al. [60]	0.39	0.29
Cathles et al. [154]	0.14–0.36	0.14–0.36
Pétron et al. [57]	N/A	0.60

4.2.1. Shale gas is better than coal and oil for climate change

(i) Comparison of the carbon footprint of conventional gas and shale gas
Stephenson et al. [86] estimated that shale gas typically has a “well-to-wire” (WtW) emissions intensity about 1.8–2.4% higher than conventional gas, arising mainly from higher methane releases in well completion. Even using extreme assumptions, it was found that WtW emissions from shale gas need be no more than 15% higher than conventional gas if flaring or recovery measures are used. In all cases considered, the WtW emissions from burning natural gas to generate electricity are significantly lower than those of coal [86] (Fig. 23). In Stephenson's study, the emissions of gas production have been modeled, so as to eliminate site-specific factors to compare gas production methods on an equal footing. In this way, parameters common to both methods of production can be held constant, while allowing those parameters which differentiate unconventional gas and conventional gas production to vary [86].

(ii) Comparison carbon footprint of shale gas and coal in electricity
Jiang et al. [43] estimated the life cycle of greenhouse gas emissions of Marcellus shale gas to be 63–75 g CO_2e/MJ with an average of 68 g CO_2e/MJ of gas produced. There is significant uncertainty in their Marcellus shale greenhouse gas emission estimates due to eventual production volumes and variability in flaring, construction and transportation. However, natural gas from the Marcellus shale has generally lower life cycle greenhouse gas emissions than coal for production of electricity in the absence of any effective carbon capture and storage processes, by 20–50% depending upon plant efficiencies and natural gas emissions variability [43] (Fig. 25). In their study, Jiang et al. compared the emissions

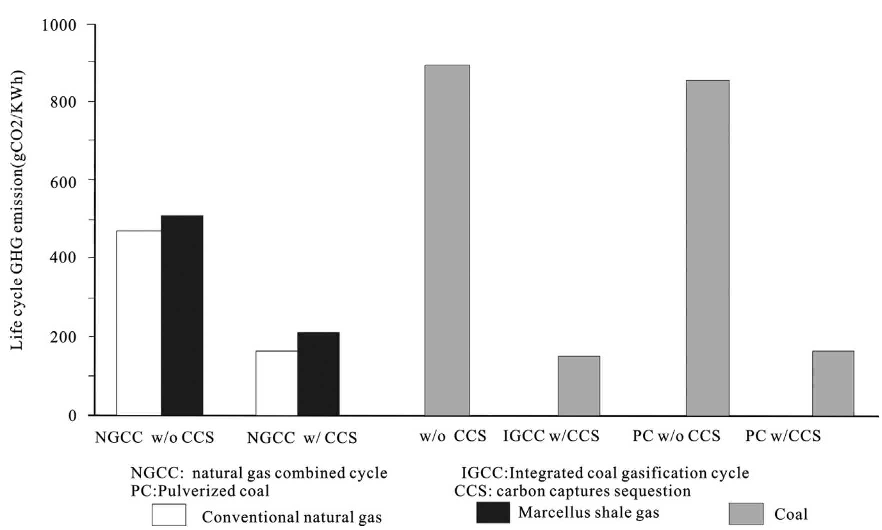

Fig. 25. Comparison of life cycle greenhouse gas emissions from Marcellus shale gas and coal for use in electricity production.
Source: Ref. [43].

associated with using Marcellus shale gas in a natural gas combined cycle (NGCC) power plant (efficiency of 50%) and the emissions from using coal in pulverized coal (PC) plants (efficiency of 39%) and integrated gasification combined cycle (IGCC) plants (efficiency of 38%). They also compared the life cycle emissions of electricity generated in power plants with carbon capture and sequestration (CCS) capabilities (efficiency of 43% for NGCC with CCS; efficiency of 30% for PC with CCS; efficiency of 33% for ICGG with CCS) [43].

In older plants, Cathles et al. [154] estimated 60% and 30% efficiency for natural gas and coal based generation of electricity respectively. Relatively low-cost 60% efficient generators using natural gas are commonly available (e.g. Siemens). When both fuels are used to produce electricity (MJe), the greenhouse impact of natural gas is only as bad as coal if a very high methane leakage rate of 7.9% and a short global warming impact period of 20 years are selected. If the comparison is based on the heat content of the fuels, the top (green) portion of the column is doubled in length, and gas becomes twice as bad as coal from a greenhouse perspective. Assuming more realistic estimates of gas leakage rates and using the 100 year GWP factor (of 33 g of greenhouse gas-equivalent CO_2 per gram of methane released to the atmosphere) which captures the contrast in atmospheric lifetimes of CO_2 and natural gas, shale gas has a much smaller global warming impact than coal. For leakage rates less than 2%, the impact of shale gas approaches one third that of coal, and methane leakage (top green bar) is an insignificant part of the greenhouse forcing compared to the CO_2 released during combustion (bottom blue part of bar) [154] (Fig. 26).

(iii) Comparison carbon footprint of shale gas and coal and oil

By using the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model of 1.8 version [305], Burnham et al examined the current state of knowledge regarding the key CH_4 emission sources from shale gas, conventional natural gas, coal, and petroleum to estimate greenhouse gas emissions and to understand the uncertainties involved in calculating their life-cycle greenhouse gas impacts. Burnham et al. report that shale gas life-cycle emissions are 6% lower than conventional natural gas, 23% lower than gasoline, and 33% lower than coal. However, the range in values for shale and conventional gas overlap, so there is a statistical uncertainty whether shale gas emissions are indeed lower than conventional gas. The study also highlights that upstream methane leakage and venting is a key

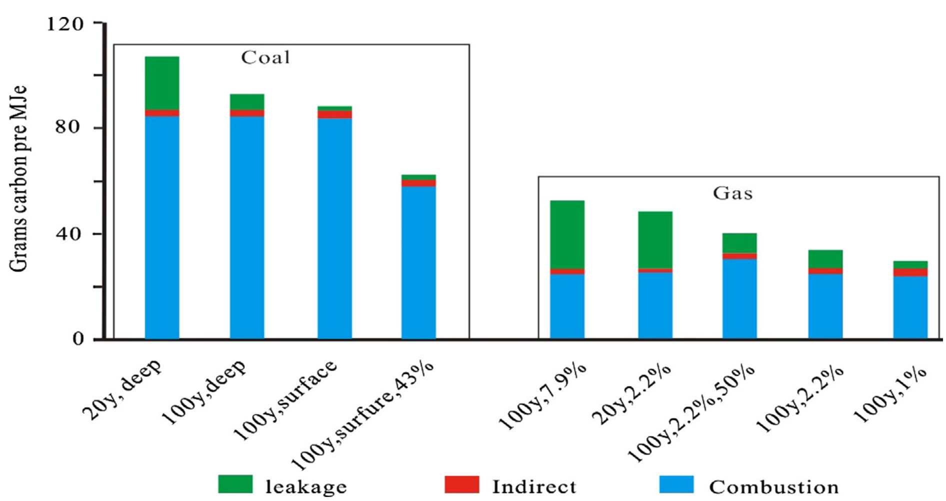

Fig. 26. Comparison of the greenhouse impact of burning natural gas to coal when the fuels are used to produce electricity.
Source: Ref. [154].

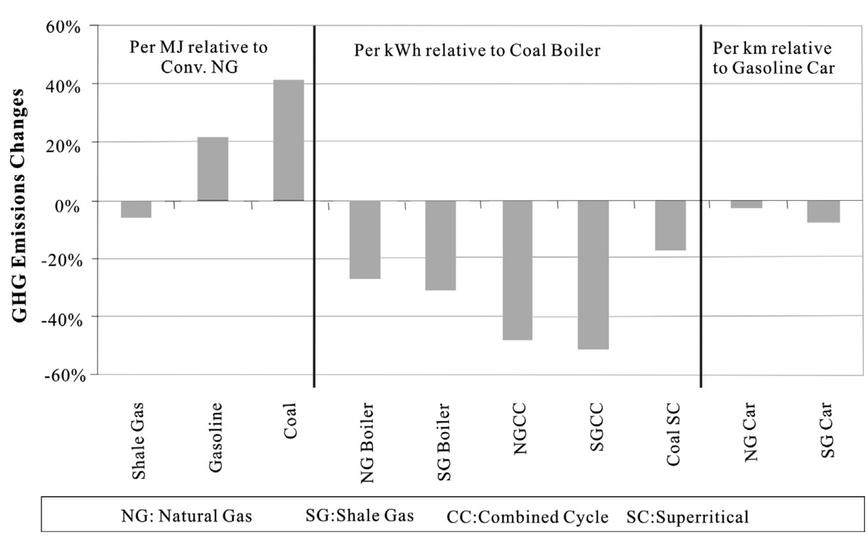

Fig. 27. Life-cycle greenhouse emissions per mega joule of fuel produced and combusted for both 100-year and 20-year time horizons.
Source: Ref. [60].

contributor to the total upstream emissions of natural gas pathways, and can significantly reduce their life-cycle benefit compared to coal or petroleum. The study found that shale gas well completion and work over emissions are a much more significant factor compared to a conventional natural gas pathway [60] (Fig. 27).

4.2.2. Shale gas might be worse than coal for climate

(i) Comparison of carbon footprint of shale gas, conventional gas, coal and oil
Howarth et al. [163] suggest that the greenhouse gas footprint of shale gas is significantly larger than that from conventional gas, oil and coal, due to methane emissions with flow-back fluids and from drill out of wells during well completion [163]. They claim that methane contributes substantially to the greenhouse gas footprint on shorter time scales, dominating it on a 20-year time horizon. On a 20-year horizon, the greenhouse footprint is 22–43% greater than that for conventional gas. On a 100-year horizon, the greenhouse gas footprint is 14–19% greater than that for conventional gas. Considering the 20-year horizon, the greenhouse gas footprint for shale gas is at least 20% greater than and perhaps more than twice as great as that for coal when expressed per quantity of energy available during combustion. Over the 100-year frame, the greenhouse footprint is comparable to that for coal: the low-end shale-gas emissions are 18% lower than deep-mined coal, and the high-end shale-gas emissions are 15% greater than surface-mined coal emissions. For the 20 year horizon, the greenhouse gas footprint of shale gas is at least 50% greater than for oil, and perhaps 2.5-times greater. At the 100-year time scale, the footprint for shale gas is similar to or 35% greater than for oil (see Fig. 28) [163].

(ii) Future scenarios of climate change impacted by the shale gas
A study by Wigley [58] took a more comprehensive look at the issue by incorporating the cooling effects of pollutants (e.g. sulfur dioxide, nitrogen oxides, and particles) associated with coal burning and by analyzing the complex climatic influences of methane, which affects other atmospheric gases (e.g. ozone and water vapor). A computer climate model known as MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) that simulates changes in atmospheric levels of greenhouse gases and their influences on global climate reported a shift from coal to gas would reduce emissions of carbon dioxide, but this shift would slightly accelerate climate change through at least 2050, even if no methane leaked from natural gas operations (Fig. 29). For example, a 50% reduction in coal and a corresponding increase in natural gas use would lead to a slight increase in worldwide warming for the next 40 years of about 0.1° Fahrenheit (less than 0.1 °C). To assess the impacts of fugitive methane, Wigley [58] analyzed the impacts of leakage rates from 0 to 10%, rather than try to assign a fixed percentage to methane leaks from natural gas operations and found that natural gas might have more of a negative climatic impact than coal if methane leaks would be over 2% [58]. However, as shown in Table 9, over half of estimates of methane emission for upstream plus midstream from shale gas are over 2%. In addition, with the exception of the estimate by Pétron et al. [57], all of these upstream emissions for unconventional gas are based on

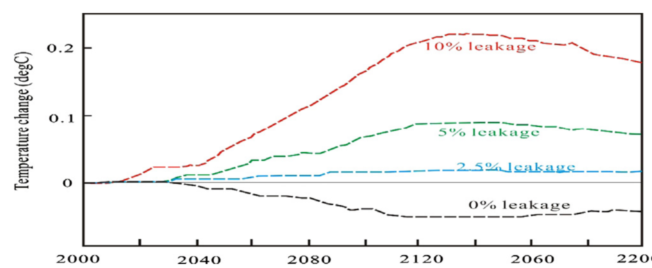

Fig. 29. The effects of different methane leakage rates on global-mean temperature. The top four curves (CH_4 component) show the effects of methane concentration changes.
Source: Ref. [58].

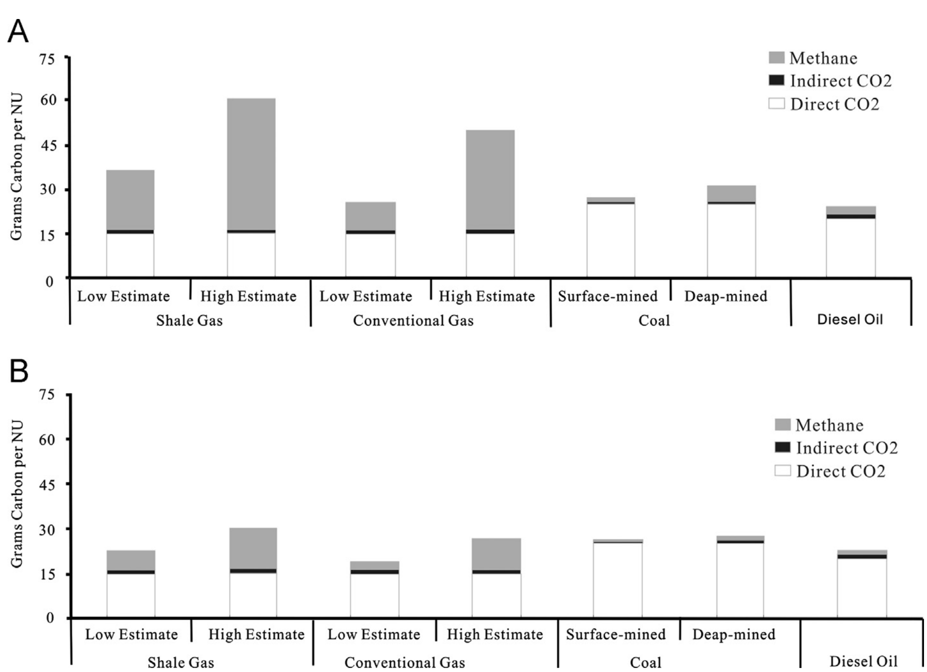

Fig. 28. Comparison of greenhouse gas emissions from shale gas with low and high estimates of fugitive methane emissions, conventional natural gas with low and high estimates of fugitive methane emissions, surface-mined coal, deep-mined coal, and diesel oil. (A) 20-year time horizon and (B) 100-year time horizon.
Source: Ref. [163].

sparse and poorly documented data. The study by Pétron et al. [57] measured fluxes from an shale gas field – at the landscape scale – over the course of a year, and is a robust estimate [306]. Pétron et al. reported an estimated loss of 2.3–7.7% for upstream plus midstream emissions from shale gas [57]. The combination Wigley's study and the estimates of fugitive methane indicate that shale gas might be worse in climate change terms than coal in the future.

Table 9
Estimates of methane emissions from upstream (at the well site) plus midstream (at gas processing plants) of shale gas.
Source: [306].

Researchers	Shale gas (the percentage of methane produced over the lifecycle of a well)
Howarth et al [163]	3.3% (mean, range = 2.2–2.4%)
EPA [72]	3.0%
Jiang et al. [43]	2.0%
Hultman et al. (2011)	2.8%
Stephenson et al. [86]	0.6%
Burnham et al. [60]	1.3%
Cathles et al. [154]	0.9%
Pétron et al. [57]	4.0% (mean, range = 2.3–7.7%)

4.3. Induced-earthquakes

4.3.1. Fluid-induced earthquake

Injection or extraction of fluid at depth alters the stresses and strains on the earth's crust, which can induce earthquakes. Below a few kilometers depth, the earth's crust is everywhere stressed. Those natural stresses put faults close to failure. The injection, which forces fluid along faults and fractures relieves the effective stress, triggering earthquakes more likely [96,307]. According to the USGS, some selected examples of human induced earthquakes, large enough to be felt and which may cause damage are shown in Table 10.

A series of studies [42,65,117,309–312] indicate that the fracking drilling technique used to tap shale gas might cause earthquake. As large volumes of fluid are injected during disposal, it may trigger large earthquakes inducing damage [117,308]. In addition to natural gas, the injection of wastewater into the subsurface can cause earthquakes [308,313].

4.3.2. Case study of hydraulic fracturing induced-large earthquakes

USGS experts take a regional approach to explore changes in the rate of earthquake occurrence in the midcontinent (defined here as 85° to 108° West, 25° to 50° North) using the USGS

Table 10
Examples of induced earthquakes.
Sources: [308].

Time	Location	Earthquake (magnitude)	Causes
2011	Youngstown, Ohio	M4.0	Fluid injection
2010–2011	Arkansas	M4.7	Fluid injection
2008–2009	Dallas Airport	M3.3	Fluid injection
	Geysers Geothermal Field (M4.6),	M4.6	Injection-enhanced production
	Italy and many others	Lake Mead (M5), Koyna (M6.3), Oroville (6.1) Tadjikistan	Water reservoirs
1976–1984	Gazli, Uzbekistan,	M7.2	Gas recovery
1962–1966	Rocky Mountain Arsenal	M5.3, 1967	Fluid injection
1945–1995	Rangely, CO	M4.9, 1995	Injection experiments

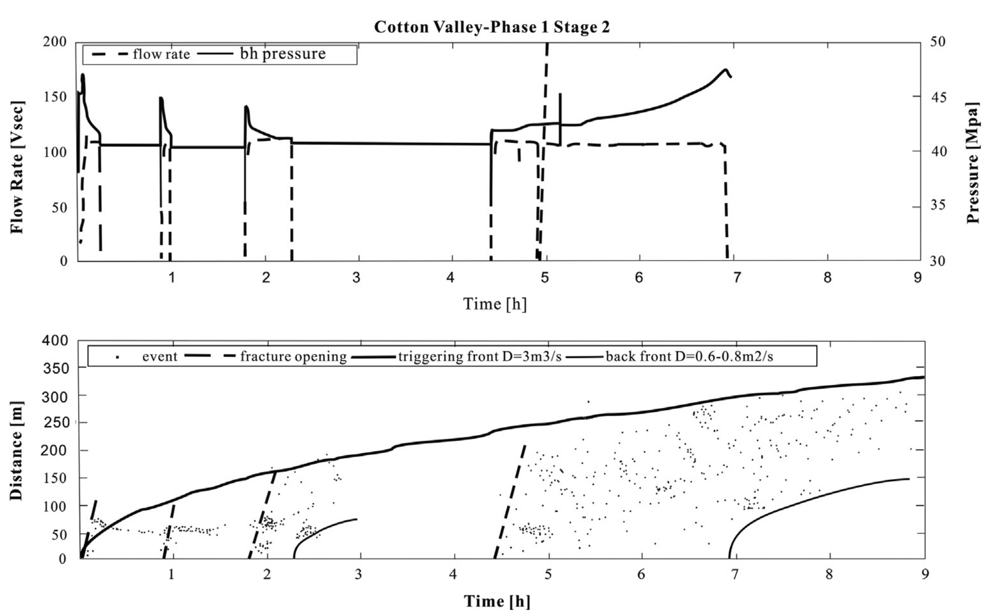

Fig. 30. Hydraulic fracturing induced microseismicity at the Carthage Cotton Valley gas field (event location courtesy of James Rutledge). Top: borehole pressure (measured at the injection domain) and fluid flow rate. Bottom: r–t plot* of induced microseismic events (upper parabolic line is a diffusion type approximation of the triggering; lower lines – back fronts; straight lines – fracture opening and reopening and correspondingly, linear with time triggering fronts propagation). $r_t = \sqrt{4\pi Dt}$ *: corresponds to the upper bound of the cloud of events in the plot of r versus t (so-called r–t plot).
Source: Ref. [67].

Preliminary Determination of Epicenters and National Seismic Hazard Map catalogs. These catalogs appear to be complete for M (magnitude) ≥ 3 since 1970. From 1970 through 2000, the rate of $M \geq 3$ events averaged 21 ± 7.6/year in the entire region. This rate increased to 29 ± 3.5 from 2001 through 2008. In 2009, 2010 and 2011, 50, 87 and 134 events occurred, respectively. They contend that the modest increase that began in 2001 is due to increased seismicity in the coal-bed methane field of the Raton Basin along the Colorado–New Mexico border west of Trinidad, Colorado. The acceleration in activity that began in 2009 appears to involve a combination of source regions of oil and gas production, including the Guy, Arkansas region, and in central and southern Oklahoma. In Oklahoma, the rate of $M \geq 3$ events abruptly increased in 2009 from 1.2/year in the previous half-century to over 25/year. This rate increase is exclusive of the November 2011 M 5.6 earthquake and its aftershocks. A naturally-occurring rate change of this magnitude is unprecedented outside of volcanic settings or in the absence of a main shock, which were not present in this region. USGS experts conclude these seismicity rate changes almost certainly manmade [314].

In addition, Frohlich et al. [311] examines seismograms and felt reports for the 25 April 2010 Alice, Texas, earthquake and explores its possible relationship with gas and oil production in the Stratton field. They conclude it is plausible, although not proven definitively, that production in the Stratton field contributed to the occurrence of this and an earlier, similar earthquake that occurred on 24 March 1997 [312].

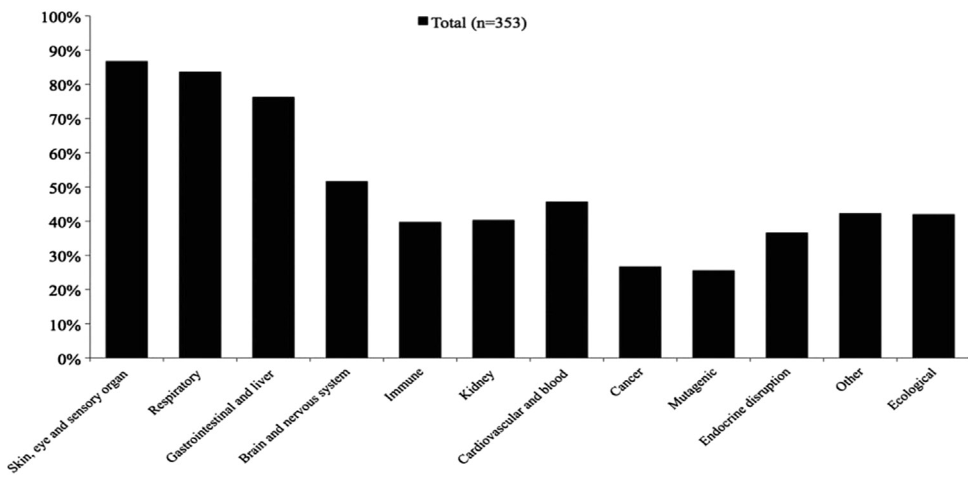

Fig. 32. Profile of possible health effects of chemicals with CAS numbers used in natural gas operations.
Source: Ref. [64].

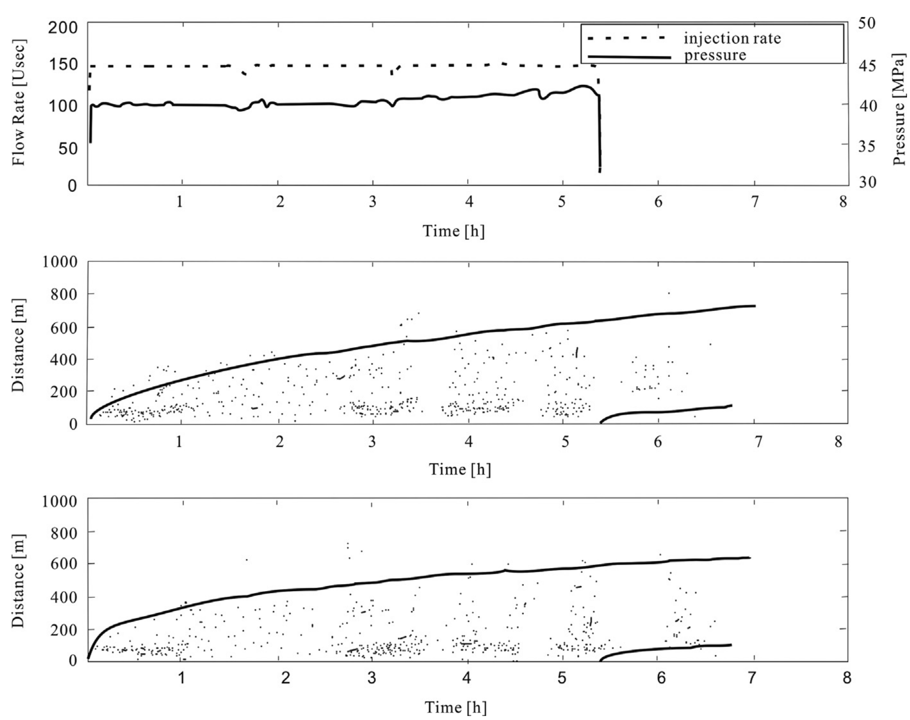

Fig. 31. Hydraulic fracturing induced microseismicity in Barnett Shale (data courtesy of Shawn Maxwell, Pinnacle Technologies). Top: borehole pressure (measured at the injection domain) and fluid flow rate. Middle and bottom: the *r–t* plot of induced microseismic events with different envelopes (in the middle – a diffusion type approximation of the triggering ($t^{1/2}$); dashed line – a possible indication of a back front; bottom: a cubic root parabola ($t^{1/3}$) better matching the data). *Note*: $r_t = \sqrt{4\pi Dt}$: corresponds to the upper bound of the cloud of events in the plot of *r* versus *t* (so-called *r–t* plot).
Source: Ref. [67].

Table 11
The best practices proposed by IEA.
Source: [68].

Measure, disclose and engage
Integrate engagement with local communities, residents and other stakeholders into each phase of a development, starting prior to exploration; provide sufficient opportunity for comment on plans, operations and performance, listen to concerns and respond appropriately and promptly
Establish baselines for key environmental indicators, such as groundwater quality, prior to commencing activity, and continue monitoring during operations
Measure and disclose operational data on water use, on the volumes and characteristics of waste water and on methane and other air emissions, alongside full, mandatory disclosure of fracturing fluid additives and volumes
Minimize disruption during operations, taking a broad view of social and environmental responsibilities, and ensure that economic benefits are also felt by local communities
Watch where you drill
Choose well sites so as to minimize impacts on the local community, heritage, existing land use, individual livelihoods and ecology
Properly survey the geology of the area to make smart decisions about where to drill and where to hydraulically fracture: assess the risk that deep faults or other geological features could generate earthquakes or permit fluids to pass between geological strata
Monitor to ensure that hydraulic fractures do not extend beyond the gas-producing formations
Isolate wells and prevent leaks
Put in place robust rules on well design, construction, cementing and integrity testing as part of a general performance standard that gas bearing formations must be completely isolated from other strata penetrated by the well, in particular freshwater aquifers
Consider appropriate minimum-depth limitations on hydraulic fracturing to underpin public confidence that this operation takes place only well away from the water table
Take action to prevent and contain surface spills and leaks from wells, and to ensure that any waste fluids and solids are disposed of properly
Treat water responsibly
Reduce freshwater use by improving operational efficiency; reuse or recycle, wherever practicable, to reduce the burden on local water resources
Store and dispose of produced and waste water safely
Minimize use of chemical additives and promote the development and use of more environmentally benign alternatives
Eliminate venting, minimize flaring and other emissions
Target zero venting and minimal flaring of natural gas during well completion and seek to reduce fugitive and vented greenhouse-gas emissions during the entire productive life of a well
Minimize air pollution from vehicles, drilling rig engines, pump engines and compressors
Be ready to think big
Seek opportunities for realising the economies of scale and co-ordinated development of local infrastructure that can reduce environmental impacts
Take into account the cumulative and regional effects of multiple drilling, production and delivery activities on the environment, notably on water use and disposal, land use, air quality, traffic and noise
Ensure a consistently high level of environmental performance
Ensure that anticipated levels of unconventional gas output are matched by commensurate resources and political backing for robust regulatory regimes at the appropriate level, sufficient permitting and compliance staff, and reliable public information
Find an appropriate balance in policy-making between prescriptive regulation and performance-based regulation in order to guarantee high operational standards while also promoting innovation and technological improvement
Ensure that emergency response plans are robust and match the scale of risk
Pursue continuous improvement of regulations and operating practices
Recognize the case for independent evaluation and verification of environmental performance

4.3.3. The evaluation of spatio-temporal dynamics of hydraulic fracturing induced microseismicity

Propagation of a hydraulic fracture is accompanied by the creation of a new fracture volume, fracturing fluid loss and its infiltration into reservoir rocks as well as diffusion of injection pressure into the pore space of surrounding rocks and inside the hydraulic fracture. Some of these processes can be seen from features of spatio-temporal distributions of the induced microseismicity.

During the initial phase of the hydraulic fracture growth, the process of the fracture opening is dominant. This can lead to a linear expansion of the triggering front over time. If the injection pressure drops, the fracture will close. A new injection of the treatment fluid leads to reopening of the fracture and thus, to resumption of the linear propagation of the triggering front. A long-term fluid injection leads to the domination of diffusional fluid loss processes. The growth of the fracture slows down. After termination of the fluid injection the seismicity is mainly triggered by the process of the pressure relaxation in the fractured domain. Correspondingly, the back front of the induced microseismicity can be observed. Fig. 30 shows an example of data demonstrating all the mentioned features of the induced seismicity during hydraulic fracturing [67].

Shapiro and Dinske estimated that microseismic features of hydraulic fracturing in Barnett Shale correspond to non-linear pressure diffusion in a medium with permeability very strongly enhanced by a fluid injection. It seems that the volumetric (possibly tensile) opening of preexisting fractures embedded into an extremely impermeable compliant matrix is the dominant mechanism controlling the dynamics of the induced microseismicity. This process can be denoted as a 3D volumetric hydraulic fracturing [67] (Fig. 31).

4.4. Health impacts

Public health was not brought into considerations for shale gas extraction at earlier stages. As a consequence, critical information about potential environmental and public health impact of the technology is lacking to address regulatory and public concerns especially for workers employed in the industry [15,123,315,316]. Although there is limited information on the health impacts of shale gas extraction [64,317,318], there is some evidences from studies in the US Midwest and Pennsylvania where drilling is taking place, [46,88]. Researchers are struggling to explore the potential health impacts of hydraulic fracturing.

A study by Colborn et al. [64] identified 632 chemicals used in shale gas operations. Literature searches were conducted to determine potential health effects of the 353 chemicals identified by Chemical Abstract Service (CAS) numbers [64]. As shown in Fig. 32, more than 75% of the chemicals on the list can affect different organ systems in the body. More than 50% chemicals

indicate effects on the brain and nervous system. Health categories that reflect chronic and long-term damage comprise the middle portion of Fig. 32. These include the nervous system (52%), the immune system (40%), kidney (40%), and the cardiovascular system and blood (46%). More than 25% of the chemicals can cause cancer and genetic damage or mutations. Notably, 37% of the chemicals can affect the endocrine system that encompasses multiple organ systems including those critical for normal reproduction and development. The category of "other" is more common, and includes effects on weight, teeth, and bone and the ability of a chemical to cause death. These chemicals therefore can simultaneously express their toxicity in a varieties of way [174]. It also should be pointed out that more than 40% of the chemicals have been found to have ecological effects, indicating that they can harm aquatic and other wildlife which could impact environmental sustainability (Fig. 32)

5. Concluding remarks

By using horizontal drilling and hydraulic fracturing technology, shale gas has grown rapidly from almost nothing at the beginning of this century to near 40% of natural gas production in 2012. This astonishing surge has transformed the US energy scenarios. With the shale gas boom, US has moved in less than a decade from being one of the world's biggest importers of gas to being self-sufficient and even preparing to become an exporter. The boom also lowered the US domestic natural gas price. US domestic natural gas price in the first half of 2012 was approx. $2 per million BTU, compared with Brent crude, the world benchmark price for oil, about $80–100/barrel, or $14–17 per million BTU. Partly because of an increase in gas-fired power generation in response to US low gas price, the fall of carbon emission from fossil-fuel combustion between 2006 and 2012 in US is more compared to any other country.

Needless to say, extraction of natural gas from rock shale formation in the US has been an energy revolution. However, this revolution in its tracks would be curbed and even be halted, if the environmental risks posed is not managed effectively [42,68]. The technique uses lots of water, and can cause pollution in several ways. Fugitive methane during the entire process of exploration and production makes the effects of shale gas on climate change more controversial. Furthermore, fracking might induce earthquakes. However, these risks can be managed by best practices [35,65,68], as proposed by the IEA (Table 11).

Adoption of best practices could increase the cost of a typical well by about 7%. This is a small price to pay for the protection of environment and the health of a promising industry. In addition, this would still leave huge profits for the companies, as natural gas could be by far the fastest growing fuel, with overtaking coal as the US's second largest source of energy between 2010 and 2035 [143]. If the industry ignored the environmental concerns, the entire industry would be damaged. Indeed, some areas have suspended or even banned shale gas exploration. On May 16, 2012, Vermont Governor Peter Shumlin signed a bill to make it the first US state to ban the controversial hydraulic fracturing. "This bill will ensure that we do not inject chemicals into groundwater in a desperate pursuit for energy," Shumlin said and called Vermont set an example for other states. Given that few natural gas resources in shale deposit of Vermont was discovered, its ban may be largely symbolic. But if other states follow the ban, it might be a big loss for the whole industry. This is not out of the realm of possibility. Other areas, including New Jersey and New York, have also issued moratoriums on new developments [68–72].

Best practices are currently being applied by some producers in some locations, but not by all producers in all locations [24,35,68,140]. Enforcing strong regulations is necessary to ensure broader adoption of these practices and to minimize risk to the environment. Robust regulatory oversight is an important ingredient to assure environmental and public protection. New stringent regulations are demanded to prevent loss of an historic opportunity to provide cheaper and cleaner energy to meet the world consumption, as well as to usher in the future growth of shale gas industry.

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